INNOVATIVE HYBRID FRP/STEEL SPLICE DETAILS FOR MODULAR BRIDGE EXPANSION JOINTS

By

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ABSTRACT

Bridge expansion joints are directly subjected to traffic load, and thus prone to premature fatigue failure. Replacement of components such as modular bridge expansion joints is typically done in a staggered schedule to minimize traffic blockage. Field splices are used to connect the successively installed segments. These splices typically include a combination of field welding or bolting, and experience has shown that they often fail due to fatigue cracking.

This thesis reports the investigation of hybrid FRP/steel splice details that avoid the use of field welding.

Two configurations have been examined: A GFRP pultruded square tube section, adhesively bonded to the soffit of the spliced beam, consists the moment resisting component in one configuration, whereas the other takes advantage of two series of FRP plates for this purpose. Bolted steel plates splice the beam through web in both cases. The behaviour of these details has been studied extensively under vertical static loads. The effect of several parameters including bond length, FRP end shape, bond surface treatment, adhesive, etc. for each detail has been investigated. A three-dimensional, non-linear finite element model has been developed for each detail and validated using the experimental results.

The bond strength of two adhesives was investigated experimentally using double shear lap splice tests.
A new method is proposed to analyze the strength of the splice details. This method is based on the results obtained from shear lap splice tests and the verified finite element model developed for the splice detail. The finite element model could thus be used for further parametric studies. More experiments, however, are statistically required before using this model with confidence.

The fatigue behaviour of one of the promising splice details has been investigated both experimentally and numerically. A special fatigue test set-up has been designed and used successfully for this purpose. Two fatigue tests to 1,000,000 cycles were run. One failed at 719,347 cycles and the other survived 1,000,000 cycles. The predicted fatigue life as per the developed model was 871,840 cycles. More experiments are required to understand the fatigue behaviour of the splice detail under various stress ranges.
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CHAPTER 1

INTRODUCTION

1.1 MODULAR BRIDGE EXPANSION JOINTS

Bridges are being designed with ever-increasing spans and require accommodation of bridge deck movement due to thermal expansion and contraction, creep and shrinkage, substructure settlements, live loads, etc.

Modular bridge expansion joints are designed to accommodate bridge deck movements greater than 100 mm. Movement should be accommodated in all six degrees of freedom, i.e. translation in all three directions and rotations about all three axes (AASHTO LRFD Bridge Design Code 2007; Article 14.5.6.9.2). More recently, they have been proposed as a means to prevent bridge girders from pounding in the case of strong earthquakes (Chouw and Hao 2009).

Modular bridge expansion joints were first developed and patented by Maurer Söhne Group (Europe) in the 1960’s. The original patent is now expired and there are several manufacturers involved in this field world-wide. Modular bridge expansion joints are proprietary products and no standard is currently available for their manufacture (NCHRP Report 467). More countries are including minimum performance requirements for modular bridge expansion joints in their national bridge codes.
Modular bridge expansion joints consist of several centre-beams (in Europe called “lamella” beams) transverse to the longitudinal axis of the bridge [Figures 1-1 and 1-2]. They are typically I-shapes or heavy rail sections and are separated by elastomeric seals. The number of centre-beams is determined by the maximum opening required for the joint system and the maximum opening capacity of the elastomeric seal. Edge-beams are typically angle-sections embedded securely in the bridge deck concrete.

Centre-beams and edge-beams are continuous beams supported by longitudinal support-beams. The typical span range is between 0.8 and 1.4 m (NCHRP Report 467). Although spans up to 2.2 m have been reported (Ancich et al. 2006), longer spans can result in a significant reduction in fatigue resistance of the system (Crocetti and Edlund 2003). Some U.S. states have already limited centre-beam spans to a maximum of 1 m.

The support-beams slide into support boxes, which are securely embedded into the bridge deck concrete. Bearings, springs, stirrups, yokes, etc. regulate the movements in the expansion joint.

Common types of modular bridge expansion joints include the Welded-Multiple-Support-Bar system [Figure 1-2], and the Single Support Bar system [Figure 1-3] (AASHTO LRFD Bridge Design Code 2007; Article 14.5.6.9.1).

The AASHTO LFRD Bridge Code requires a staged construction for modular bridge expansion joints longer than 18 m. In addition, when replacing prematurely failed modular bridge expansion joints, a staged construction is normally adopted to minimize
the adverse effect of traffic blockage. Field splices are thus required to splice the segments of the modular bridge expansion joint centre-beams.

1.2 STATEMENT OF THE PROBLEM

Being metallic components directly subjected to traffic loads, modular bridge expansion joints are susceptible to fatigue. Premature failure of joints causes significant financial loss to both the bridge owner and users. Modular bridge expansion joints are expensive components (approximately $333 per metre for every 25 mm of movement capacity). The cost for a large, multiple-lane bridge with large required movement could approach $1 million (NCHRP Report 467). Replacement of such superstructure components also requires closure of traffic lanes, if not the entire bridge, which means even more financial loss.

Splice details can be either “moment-resisting” or of the “hinge-type”. Two types of moment-resisting splice details, namely the “full penetration weld splice” [Figure 1-4] and “fish-plate splice” [Figure 1-5], in addition to one hinge-type “bolted splice” detail [Figure 1-6] have already been used as field splice details for modular bridge expansion joint centre-beams (NCHRP Report 402). Their performance has been discussed in detail in NCHRP Report 402.

The Ministry of Transportation of Ontario (MTO) is not satisfied with the current available details for field splices. Modular bridge expansion joints continue to fail
prematurely under fatigue, especially in centre-beam splices, causing significant financial loss (MTO correspondence). A research program was initiated and funded by the MTO to investigate new details for fatigue resistant centre-beam field splices.

There is a trade-off between the moment-resisting and hinge-type splice. Theoretically, there is no bending stress (and therefore no fatigue cracking) in a hinge-type splice detail. However, it can increase the stress level in the adjacent details of the modular bridge expansion joint, particularly the centre-beam to support-beam connection. As a result, designers will usually reduce the length of the span having this type of splice.

In addition, despite the theoretical prediction of no fatigue cracking, evidence of fatigue failure has been reported in hinge-type splices (NCHRP Report 402/467; MTO correspondence).

A moment-resisting splice is thus perceived as preferable as the focus of fatigue resistance will remain on the splice itself, with a resulting lower probability of fatigue failure in other components of modular bridge expansion joint as a system.

1.3 Fibre Reinforced Polymers for Strengthening Steel Members

After many years of being successfully used in the aerospace, naval, automotive, and recreational industries, fibre reinforced polymer (FRP) material was introduced commercially to the civil engineering industry during the late 1980’s (Bank 2006). The majority of the applications were focused on concrete structures where FRP material is
used in the form of rebars, sheets, and plates for construction, rehabilitation and strengthening purposes. A significant amount of research has resulted not only in general acceptance of FRP as an advanced construction material, but also provided enough supporting data to develop required codes and standards (Teng et al. 2002; Bank 2006). It was, however, not until the late 1990’s that some researchers started to investigate potential applications for FRP material in steel structures.

Among the most commonly available FRP products, namely Aramid-FRP, Glass-FRP, and Carbon-FRP, the application of the last two has been investigated for steel structures. FRP has high strength-to-weight ratio, excellent durability, and good fatigue resistance. The factors that favour using adhesively bonded FRP systems for strengthening and rehabilitation as compared to welding or bolting steel plates include: no disturbance of the metallurgical properties of the substrate due to welding; no creation of residual stresses due to welding; and a more uniformly distributed stress.

FRP in the form of thin-walled pultruded sections of I-, box-, channel-, and angle shaped sections has also been used in the construction industry for more than 30 years. Currently, there is no standard governing the manufacture or the design of structures made of these pultruded sections (Bank 2006).

Ever-increasing application of FRP products has resulted in a significant decrease in its price. However, it is still a relatively expensive material. Nevertheless, the initial high product cost can be offset by the savings in labour and machinery, minimum interference with the daily operation of system and its lower life maintenance cost.
1.4 PROPOSED SOLUTION

Due to the above-mentioned advantages, FRP is proposed as a means to splice modular bridge expansion joint centre-beams. After consulting with several companies involved in the fabrication of modular bridge expansion joints in Ontario and Quebec, two moment-resisting details [Figures 4-1 and 4-2] have been proposed.

Figure 4-1 illustrates Splice Detail #1. A hollow square FRP section is used to splice the steel beam through its soffit. The top surface of modular bridge expansion joint centre-beam is subjected to traffic [Figure 1-1], and thus not accessible to splice. A hollow section is used instead of plate due to its higher flexural stiffness. This could help to restore the original flexural stiffness of the intact beam.

Bolted steel plates are used to splice the steel beam through its web. Two bolts are used on each side. This is similar to a hinge detail currently used by one Canadian expansion joint manufacturer. It ensures that the ends of the centre-beams are aligned so that the FRP section can be adhesively bonded to the centre-beam in the field.

The steel plates and the FRP section are proportioned so that the flexural stiffness of the spliced beam is similar to that of the intact beam.

Splice Detail #2 is illustrated in Figure 4-2. In this case, FRP plates adhesively bonded to the top and bottom flanges are used to splice the beam. Since the top surface of the modular bridge expansion joint centre-beam is not accessible, the FRP plates are bonded to the inner surface of the top flange.
1.5 **OBJECTIVES**

To the author’s knowledge, there have been no previous attempts to splice steel beams using FRP and in the proposed configurations. The behaviour of this hybrid system is not known under any design limit states. As a first step, thus, it is crucial to obtain a sound knowledge of the behaviour of these proposed details under serviceability and ultimate limit states. However, the fatigue performance of the splice detail is the most important design criteria, and an assessment of the fatigue resistance of the proposed details is also necessary.

The availability of an appropriate FRP and adhesive was found to be one of the greatest obstacles faced during this research. The adhesive bond is often the weakest component of an FRP strengthened steel member (CIRIA-C595 2004). Identifying appropriate adhesives and modeling their behaviour is an important step in developing such hybrid systems.

It is required, therefore, to develop a model of the proposed splices to further investigate the effect of all parameters involved.

The following objectives were defined and pursued under this research program:

- To experimentally measure the strength of the adhesive bond between FRP and steel for the specific materials used in this study in order to select the best adhesive for this purpose.

- To develop a verified model of the FRP-to-steel bond.
• To study experimentally the behaviour of the two proposed splice details under static and limited cyclic loads at both the serviceability and ultimate limit states.

• To develop verified models of behaviour of the two proposed splice details at serviceability and ultimate limit states.

• To conduct a preliminary study on the fatigue resistance of the splice detail exhibiting the most promising performance at serviceability and ultimate limit states.

1.6 Overview

A comprehensive review of the relevant literature is provided in Chapter 2.

Chapter 3 provides the results of an experimental study conducted to select the best adhesive for the purpose of this research. A nonlinear, three-dimensional (3-D) numerical model, using the finite element analysis technique, is developed to analyze the stress distribution within the adhesive bond and to identify the characteristic strength of the adhesives being tested.

The behaviour of the proposed splice details under static loads is studied experimentally, the results of which are discussed in Chapter 4. Splice Detail #1 was first proposed. The effect of various parameters involved was examined using an extensive experimental program. However, using the range of commercially available FRP products on the
market, Splice Detail #1 did not yield promising results. Splice detail #2 was thus proposed and tested experimentally to a limited degree within the limits of time and budget. The proposed details have been modelled three-dimensionally, using finite element analysis technique, which is used in a complementary parametric study (Chapter 5).

The preliminary assessment of the fatigue resistance of Splice Detail #2 is discussed in Chapter 6. A fatigue test set-up is developed and two fatigue tests were run. The experimental results are compared with a simple fatigue life prediction method.
1.7 REFERENCES


MTO correspondence (2008-2009). *Private correspondence between Ministry of Transportation of Ontario and Queen’s researchers regarding the project.*


Figure 1-1: Modular bridge expansion joint installed in Burlington Skyway Bridge

(Rameshni, Summer 2008)

Figure 1-2: Modular bridge expansion joint; Welded-Multiple-Support-Bar system
Chapter 1  Introduction

Figure 1-3 - Modular bridge expansion joint; Single-Support-Bar system

Figure 1-4 - Full penetration weld splice detail (moment-resisting)
Chapter 1  Introduction

Figure 1-5- Fish plate splice detail (moment-resisting)

Figure 1-6- Bolted splice detail (hinge-type)
CHAPTER 2

LITERATURE REVIEW

2.1 MODULAR BRIDGE EXPANSION JOINTS

Several research studies have been performed on modular bridge expansion joints. Dexter et al. [NCHRP Reports 402 and 467] completed an exhaustive study on modular bridge expansion joint performance. The major problems associated with modular bridge expansion joints have been categorized by Dexter et al. [NCHRP Report 402] into four main groups:

I. Problems associated with the poor design of the joint

II. Problems associated with improper installation

III. Wear and tear of the elastomeric parts

IV. Fatigue cracking of the joint components or their connections

NCHRP Report 467 dealt with durability problems other than fatigue. Due to the proprietary nature of modular bridge expansion joints, minimum performance requirements were proposed. Two pre-qualification and acceptance tests, namely “opening movement vibration” and “seal push out”, were proposed. In addition, guidelines for the materials, fabrication, construction, and installation of modular bridge expansion joints were also provided in this report.
NCHRP Report 402 dealt in detail with the fatigue performance of modular bridge expansion joints. The centre-beam to support-beam connection was identified as the critical detail (the weakest link) with respect to fatigue. NCHRP Report 402 provides a detailed discussion on the loading requirements for modular bridge expansion joints as per the AASHTO LRFD Bridge Design Code in comparison with the Eurocode requirements. The infinite-life fatigue design philosophy with the AASHTO LRFD fatigue truck wheel load was adopted for modular bridge expansion joints.

The design load consists of vertical and horizontal (20% of vertical) loads simultaneously applied to the top flange of the centre-beam as two wheel loads with transverse widths of 510 mm in accordance with the AASHTO LRFD Bridge design code, Article 3.6.1.2.2. The pair of wheel loads should be so positioned to give the worst-case stress range for each particular detail.

Although the target fatigue life for modular bridge expansion joints has been taken as 75 years, it was shown that a 25-year typical life for a modular bridge expansion joint would easily result in a number of loading cycles greater than that of the associated constant amplitude fatigue limits.

The fatigue limit axle load and the dynamic response of the modular bridge expansion joint were identified as the two critical factors affecting the fatigue resistance.

The loading on the centre-beam is a function of the “tire pressure” times the patch size. This fact mitigates the uncertainty in the fatigue limit state axle load. It was thus recommended to adopt the same loading requirements as per the AASHTO LRFD Bridge
Design Code. The only major modification deemed necessary was for the axle load to be divided by two. The axle load, as per the AASHTO LRFD Bridge Design Code, was reported to be just a simplification of a tandem axle and it is each of these axles that the centre-beam would experience in practice.

Fatigue test procedures were proposed to derive the stress-life characteristic curve for modular bridge expansion joints. At least 10 centre-beam to support-beam subassemblies of the modular bridge expansion joint, each consisting of a three-span centre-beam supported by four support-beams, should be tested. The loading is applied upward to the alternate spans. The authors indicated that using test samples with fewer than 3 spans would result in a non-conservative value of the fatigue limit.

Specimens should also be tested statically to verify structural analysis models of the joint. The model is assumed verified if the predicted static strain ranges are within ±25% of the measured strain ranges obtained during a calibration test. The authors recommend using the model to predict the nominal stress range in the expansion joint.

Once the constant amplitude fatigue limit for the modular bridge expansion joint is specified, the stress range in the critical connection for a range of similar modular bridge expansion joints, under the factored fatigue axle load as per the AASHTO LRFD Bridge specification, can be derived using the verified structural analysis model. The stress range in the critical detail under the applied loads should be less than half the constant amplitude fatigue limit to ensure the fatigue resistance of the detail.
Fatigue performance of modular bridge expansion joints has also been investigated by Agarwal (1991), Tschemmernegg (1991), Roeder (1998), Crocetti and Edlund (2003), Chaallal et al. (2006), Ancich et al. (2006), and Yagi et al. (2007). The last reference is published in Japanese and thus could not be fully consulted.

Roeder (1998) indicates that the fatigue design is quite different for modular bridge expansion joints compared to other steel components of a bridge. This is mainly due to the significantly higher number of cycles of loading it experiences. Also, the fatigue loading depends more on the dynamic nature of the applied wheel load rather than the truck weight. Describing the frequent, premature fatigue cracking observed in the modular bridge expansion joint installed in the 3rd Lake Washington Bridge, Roeder questioned the validity of the simple fatigue limit state design procedure proposed by Tschemmernegg (1991), referencing the field measurements done by Agarwal (1991).

The results of global and local modelling developed for this particular modular bridge expansion joint were provided in Roeder (1998). The model predicted the stress range in the components of the modular bridge expansion joint. The results of the dynamic analysis performed for this modular bridge expansion joint, using the global model, were also presented. A series of experimental measurements on this particular modular bridge expansion joint were also reported.

Crocetti and Edlund (2003) put further emphasis on the importance of considering dynamic behaviour. They stated that considering the effect of the axle load and the dynamic characteristics of the modular bridge expansion joint should result in a sufficient
degree of accuracy in fatigue life estimation. This excludes the special cases where the modular bridge expansion joint is placed near traffic lights or stop signs, where there is significant horizontal load due to frequent braking/acceleration, and in roadways with high slope (>10%). A modular bridge expansion joint was modelled as a single-degree-of-freedom system. Based on the results, Crocetti and Edlund (2003) proposed a total dynamic amplification factor equal to 1.7 (based on the response of the modular bridge expansion joint to the design truck travelling at 90 km/h, including the rebound effect). They recommended keeping the natural frequency of the designed modular bridge expansion joint, for vertical vibrations, well above 100 Hz to avoid higher dynamic amplification factors. This can be achieved by increasing the stiffness of the centre-beams or reducing the corresponding spans.

An increase in the axle load results in a proportional decrease in the distribution factor, as explained by Crocetti and Edlund (2003).

The results of the experimental fatigue testing (to 2 million cycles) on complete modular bridge expansion joint assemblies and subassemblies consisting of individual centre-beams and associated support-beams were also discussed in Crocetti and Edlund (2003). The samples had either two or three spans with no splices. A reduction in the associated horizontal load from 20% to 10% of the vertical load was suggested based on the field findings and the fact that these two loads were not in phase with each other.

The results confirmed the findings by Dexter et al. (NCHRP Report 402) that an S-N curve Category C is appropriate for the fatigue design of modular bridge expansion
joints. As a guideline, for multiple-support-bar modular bridge expansion joints, Crocetti and Edlund (2003) recommended using an equivalent vertical axle load equal to 60 kN with an amplification factor and distribution factor equal to 1.7 and 0.58 respectively for fatigue purposes. This means an equivalent factored axle load equal to 59.16 kN. For single-support-bar systems they recommended a higher amplification factor equal to 2. It should be noted that the recommended values were given for a centre-beam flange size of 80 mm, gap between centre-beams of 40 mm, tire patch length of 250 mm, and design truck speed of 90 km/h.

A brief introduction to modular bridge expansion joints and their typical durability problems was presented in Chaallal et al. (2006). It includes a detailed description of experimental testing conducted to derive the fatigue resistance of the modular bridge expansion joint used to rehabilitate the Jacques Cartier Bridge in Montreal, Quebec, Canada. Specimens consisted of three spans each 0.91 m. A simple linear three-dimensional (3-D) model was shown to be able to reproduce reasonably accurate results (within 25% of the experimental values).

Dynamic anomalies in modular bridge expansion joints were investigated by Ancich et al. (2006). This research was initiated to investigate the noise production mechanism in the Sydney’s Anzac Bridge, Australia. The authors took into account the possibility of lightly damped vibration in the modular bridge expansion joints after the passage of a vehicle axle. This dynamic behaviour reduced the fatigue resistance of the modular bridge expansion joints by increasing the number of effective cycles of loading.
and also by introducing higher uplift forces to the joint. This is an important factor
neglected by most current codes, as stated by the authors.

Yagi et al. (2007- in Japanese) investigated in-service fatigue performance for modular
bridge expansion joints in major highways in Japan. The research involved extensive
three-dimensional (3-D) modelling of the modular bridge expansion joint and the centre-
beam to support-beam connection.

2.2 LOADING REQUIREMENTS

2.2.1 Canadian Highway Bridge Code (CHBDC 2006)

The Canadian Highway Bridge Design Code (CHBDC 2006) does not include any
explicit requirements for modular bridge expansion joints and its design, manufacture,
and installation. Expansion joints are only mentioned in the context of design loading
requirements for different bridge components. Expansion deck joints (including modular
bridge expansion joints) are to be designed for design truck CL-625 (in Ontario CL-625-
ONT), axle #4 (175 kN) with an amplification factor equal to 1.5. There is no
differentiation made between the design truck for ultimate limit states and fatigue limit
states.

The CHBDC applies design load factors equal to 1.7 and 1 to the CL-625 truck load for
ultimate and fatigue limit states, respectively. The maximum stress range in the
component under the factored fatigue design load \((f_{sr})\) should be compared to the fatigue stress range resistance \((F_{sr})\):

\[
0.52 f_{sr} \leq F_{sr}
\]  

(2.1)

Considering infinite life fatigue philosophy for modular bridge expansion joints, the fatigue stress range resistance \((F_{sr})\) should be less than half the constant amplitude fatigue limit \((F_{srt})\):

\[
F_{sr} \leq 0.5 F_{srt}
\]  

(2.2)

No guidance has been provided as to how to distribute the wheel loads on the centre-beams. Two wheel contact areas are specified as 600 × 250 mm rectangles spaced 1800 mm centre-to-centre apart.

2.2.2 American Association of State Highway and Transportation Officials Load and Resistance Factor Design Bridge Code (AASHTO LRFD 2007)

The results of the two research projects undertaken by Dexter et al. on modular bridge expansion joints (NCHRP Reports 402 and 467) were the basis for the expansion joint provisions in the AASHTO LRFD Bridge Code. It includes a detailed set of minimum requirements for design, manufacture, and installation of modular bridge expansion joints (AASHTO LRFD 2007: Article 14.5.6.9 and Appendix A).

The design loading specified for modular bridge expansion joints at the fatigue limit states is one-half of Axle #3 of the HS-20 design truck (145 kN). The amplification factor and fatigue design load factor are set equal to 1.75 and 0.75 respectively. A different
design load (design tandem) is used to design modular bridge expansion joints under ultimate limit states. The design tandem consists of two 110 kN axles spaced 1200 mm apart. The two wheel loads are applied as two rectangle patches each $510 \times 250$ mm which are positioned 1830 mm centre-to-centre.

In addition, a distribution factor is introduced which specifies the percentage of wheel loads applied to each centre-beam. For a typical centre-beam with an approximately 100 mm flange width, the distribution factor is equal to 70%.

The maximum calculated stress range in each detail under the factored fatigue load ($f_{sr}$) should be always less than half the constant amplitude fatigue limit of the corresponding fatigue category.

### 2.2.3 Comparison

A comparison between the loading requirements to design modular bridge expansion joint under fatigue as per the above-mentioned two codes show that the Canadian Highway Bridge Design Code is significantly more stringent. The factored fatigue design load as per the AASHTO LRFD Bridge Code is a 66.6 kN ($= 145 / 2 \times 1.75 \times 0.75 \times 0.7$) axle applied to each centre-beam, whereas, the fatigue design load is 136.5 kN ($= 175 \times 0.52 \times 1.5$) axle as per the Canadian Highway Bridge Design Code. It is noteworthy that an equivalent factored axle load equal to 59.16 was recommended by Crocetti and Edlund (2003) to be used to design modular bridge expansion joints against fatigue.
2.3 Field spliced centre-beams

Fatigue resistance of the three customary centre-beam field splice details, namely full-penetration weld splice [Figure 1-4], moment-resisting fish plate splice [Figure 1-5], and hinge-type bolted splice [Figure 1-6] was discussed in NCHRP Report 402. Full penetration weld splices, if implemented according to the specifications, perform well and conform to Fatigue Category B. However this type of splice can only be made in the field for modular bridge expansion joints with just one centre-beam.

No fatigue cracking was reported during testing of hinge-type bolted splices when loading was applied to spans adjacent to the spliced span. When loading was applied to the spliced span, a very shallow crack was observed at a weld toe of one of the welded nuts at the end of the test. The authors suggest that the loading range was so high that this condition is equivalent to millions of cycles of service loads (NCHRP Report 402).

The fatigue resistance of moment-resisting fish-plate splice details can be characterised as Fatigue Category E or E’. In the tests, the loading was applied to the spans next to the spliced one. As a result, they were believed to be of not sufficient magnitude to cause fatigue cracking.

Moreover, measurement of the strains in the fish-plate splice indicated that the detail was not as effective in reducing bending stresses (by increasing the section modulus) as would be theoretically calculated. This was attributed to the shear lag effect.
Based on the results, NCHRP Report 402 recommended the hinge-type bolted splice as the appropriate way to join centre-beams in the field. They were not required to be explicitly designed against fatigue as theoretically they do not take any bending moment. The shear stresses were also believed to be too minimal to govern the fatigue design. However, more testing of splice details was recommended.

Six modular bridge expansion joints from four manufacturers were tested under fatigue in a research program reported in NCHRP Report 467. The modular bridge expansion joints were the latest models of their manufacturers at the time of testing (1999). Thus they were expected to have taken into consideration the important results and proposed modifications as per NCHRP Report 402 published in 1997. Four of the tested expansion joints had a centre-beam bolted splice designed and installed by their manufacturers prior to shipment to the testing facility. Each joint was subjected to fatigue testing to simulate a 75 year design life. Fatigue failures of the bolts or plates were reported at fatigue lives equivalent to 39 to 73 years. Fatigue failure of other components was reported at earlier ages. It was recommended by the researchers to design an improved splice detail.

### 2.4 FRP STRENGTHENED STEEL MEMBERS

FRP has been investigated as a means of strengthening different structural steel members such as beams, columns, composite girders, beam-to-column joints, etc. It has also been used to rehabilitate fatigue cracked and environmentally corroded girders. The potential
to increase the capacity of steel columns or walls against blast attacks has also been investigated. A full summary of the different application of FRP products in steel structures could be found elsewhere (CIRIA-C595 2004, Zhao and Zhang 2007, Satasivam and Zhao 2009)

Using FRP products to strengthen and rehabilitate steel beams or girders has been investigated by several researchers. Both intact beams and deteriorated ones, either alone or in composite with concrete slabs, have been investigated. Using composite steel girders has been justified in that they are the most common types of structural steel members used in bridges and buildings. The presence of a concrete slab, in addition to increasing the strength and stiffness of the girder, prevents premature failure due to local or lateral-torsional buckling.

No literature could be found by the author specifically dealing with splicing steel beams using FRP material. On the other hand, splicing steel beams could be compared, to some extent, to strengthening damaged girders. In studying this problem, some researchers simulated fatigue cracks or corrosion by cutting through the tension flange of the girder at the mid-span. This is the most similar case to a spliced beam, especially if a non-composite wide-flange section has been used in the study.

Liu et al. (2001) investigated the effect of an FRP repair system on restoring the strength and stiffness of artificially deteriorated W310×21 beams. The beams were simply supported over a 2438 mm span and loaded in three-point bending. The tension flanges of
the beams were fully removed at mid-span over a 102 mm length. High modulus carbon-FRP (CFRP) plates were used for the repair.

Two different bond lengths were investigated. In case of the shorter one, the failure mode was a sudden debonding of the CFRP laminate whereas for the longer bond length, there was a gradual debonding of the CFRP laminate starting at mid-span, and extending to the end as the load increased. It was reported that removing the tension flange did not change the beam stiffness; however, its strength was reduced to almost 50% of the intact beam. The repair systems restored 41% to 56% of the lost strength capacity of the beams.

Using a sufficient amount of standard-modulus CFRP laminates, Tavakkolizadeh and Saadatmanesh (2003) not only restored the strength capacity of a deteriorated composite girder, but also increased it by 10%. The deteriorated composite girder, with 100% loss in tension flange at mid-span, had an extra gain in stiffness of 86% (with respect to the intact beam). The failure mode was reported to be a complete debonding of CFRP laminate associated with crack propagation.

Shaat (2009) studied the effect of CFRP to rehabilitate deteriorated composite beams. The deterioration was simulated by removing the tension flange at mid-span. The adhesive was SP systems Spabond 345 as recommended by Schnerch et al. (2007). The effect of various bond lengths, amount, and modulus of CFRP laminates used was investigated. It was shown that using CFRP material with a higher modulus resulted in higher stiffness and strength of the repaired system, though decreased its ductility. Bond length (or development length) was defined as the distance from mid-span to the end of
FRP plate (i.e. half of the total length of the FRP plate being used). In some cases the CFRP laminate length was even less than the length of the constant bending moment zone. Increasing bond length from 5% to almost 50% of the span resulted in an increase in both strength and stiffness.

Effective bond length is defined as the FRP length at which additional strength does not occur. This phenomenon was first observed and documented in FRP strengthened reinforced concrete members (Teng et al. 2002). The results obtained by Shaat (2009) do not show such an idealized phenomenon for the FRP repaired notched composite girders. However, the gain in strength decreased significantly after a bond length equal to 100 mm. This could be taken as the effective bond length for the adhesively bonded CFRP system being used.

Fam et al. (2009) reported the results of strengthening notched W100×19 beams loaded under four-point bending pattern, research done originally by Howard (2006). Two different CFRP materials (high modulus CFRP sheets and ultra-high modulus CFRP plates), were used to strengthen the beams. SP systems Spabond 345 was used in this study as recommended by Schnerch (2005). Out of the 15 beams tested, 7 had a full tension flange removed at mid-span. Two different notch sizes were used in this study. The results show that introducing the notch to the tension flange significantly reduced both stiffness and strength of the beam (40 – 70 %). Using high-modulus CFRP resulted in little increase in strength of the notched beam, although it increased its stiffness significantly. On the other hand, using ultra-high modulus CFRP material resulted in
significant increase in both stiffness and strength of the notched beams. The same pattern was observed for both notch sizes. The failure mode for high-modulus CFRP was reported to be a rupture at the notch location, whereas a debonding failure mode was observed for ultra-high modulus CFRP.

In order to take full advantage of the properties of FRP, it was suggested that FRP with mechanical properties comparable to that of steel should be used (Satasivam and Zhao 2009). Carbon-FRP (CFRP) has, thus, been used for most of the research so far. The potential application of glass-FRP (GFRP) plates to strengthen steel beams was investigated by El-Damatty et al. (2005). The test specimens did not include a notch in the tension flange. It was reported that applying GFRP sheets to the tension and compression flanges successfully increased stiffness, yield moment and ultimate strength of the sections by 15%, 23%, and 78% respectively. A methacrylate-type adhesive was reported to be used in these experiments.

Schnerch (2005) did extensive research on strengthening steel-concrete composite girders with CFRP sheets and strips. His work did not include rehabilitated notched girders. However, he studied the effectiveness of six different adhesives by comparing their corresponding development length. The development length was defined by Schnerch (2005) as the length from the end of constant bending moment zone to the end of CFRP strip. Two adhesives, namely SP systems Spabond 345 (epoxy) and Weld-On SS620 (methacrylate), had the shortest development lengths and were recommended for strengthening systems using CFRP material.
2.5 FRP PULTRUDED PROFILES

FRP in the form of thin-walled pultruded profiles of I-, box-, channel-, and angle shaped sections has been used by the construction industry for more than 30 years. At this time, there is no standard for the geometric and mechanical properties of such sections or even the design of structures made of these pultruded sections. Designers reference in-house guidelines published by the manufacturers. Guidance on how to develop such a design basis is provided elsewhere (Bank 2006). Two consensus design manuals, namely the “Structural Plastics Design Manual (ASCE 1984)” and the “Eurocomp Design Code and Handbook (Eurocomp, 1996)” has been reported to be published (Bank 2006).

Almost all commercially available structural FRP pultruded sections are made of GFRP mainly due to its lower price. There is however some research published on hybrid CFRP and GFRP I-sections (see for example: Hai et al. 2010).

The behaviour of beams and columns, made of FRP pultruded sections, has been experimentally investigated since early 1980’s (Bank 2006). GFRP pultruded square tube sections have also been used in making concrete filled tube beams and experimentally investigated (Fam & Skutesky 2006; Shawkat 2008). No literature, if any, was found on the hybrid application of FRP pultruded sections and steel structural members. Neither has it been reported for splicing purposes.
2.6 Adhesives

The adhesive is typically the weakest component of a bonded FRP-steel system. Adhesive debonding has been reported as the dominant failure mode for such systems (CIRIA-C595 2004). It is thus critical to select the most appropriate adhesive to resist the maximum stress developed in the bond. Despite its importance, only a few studies could be found in the literature focused on the adhesive.

Schnerch (2005) investigated the bond strength between CFRP and steel for six different adhesives by subjecting to four-point bending steel beams strengthened by CFRP plates adhesively bonded to the soffit of the beam. An “elimination process” was employed by Schnerch (2005) to determine the effective bond length for different adhesives being tested. The bond length was reduced in sequence for those adhesives that were able to take advantage of the full properties of the CFRP plates being used, i.e. the failure happened through rupture of the CFRP plate, rather than adhesive debonding. This range of bond length, for which there was a change in failure mode, was defined as the effective bond length for that adhesive. SP systems Spabond 345 (an epoxy-type adhesive) and Weld-on SS620 (a methacrylate-type adhesive) resulted in the shortest effective bond lengths (between 76 and 102 mm). SP systems Spabond 345 was recommended by Schnerch et al. (2007) to be used in the strengthening systems using high modulus CFRP strips. As a result, this adhesive was used in further research programs such as Howard (2006), and Shaat (2009).
Xia and Teng (2005) performed single shear pull-off tests to understand and model debonding failures for the adhesive bond between CFRP and steel substrates for three different adhesives. Little information on the type of adhesives was provided by the authors; however, it appears epoxy-type adhesives were used. It was shown that the bond strength is more dependent on the strain-to-failure of the adhesive than its shear or tensile strength. It was concluded that for adhesive layers 1 to 2 mm thick, failure is governed by debonding through the adhesive layer, whereas for adhesive layers 4 to 6 mm thick, failure is governed by delamination through the FRP. Schnerch et al. (2007) also reported a range 0.5 to 2 mm as the optimum thickness for the adhesive layer.

El-Damatty et al. (2003) investigated the bond strength between GFRP and steel for eight different adhesives including epoxy, acrylic, and methacrylate-type adhesives. Lap splice specimens were loaded in compression to failure. These results should therefore not be extended to situations where the GFRP is in tension (Zhao and Zhang 2006). However, on a qualitative basis, the results can be compared to that of other researchers. Despite being unclear in terms of the actual mechanical properties of the adhesives used, the best bond strengths were obtained for the methacrylate-type adhesive. Two methacrylate-type adhesives (MA300 and MA420 by Plexus) appear to have been used. MA420 resulted in higher bond strengths, despite having a lower modulus (≈ 50%) and slightly lower tensile strength (95%) than MA300. This can be attributed to MA420 having a significantly higher strain-to-failure (≈ 5 times) than MA300. This is consistent with the results of Xia and Teng (2005). It is also worth noting that Hart-Smith (1973) identified the ultimate
shear strain of the adhesive as the key parameter in its strength which is consistent with the above-mentioned conclusions.

**2.7 Surface Preparation Method**

The strength of adhesively bonded FRP-steel systems depends not only on the characteristics of the adhesive but also on the mechanical properties of the substrates and the preparation method used for the bond surfaces. Schnerch et al. (2007) provides recommended installation guidelines for the case high-modulus CFRP material. It was recommended to wash the steel surface with acetone or other appropriate solvents to ensure there is no grease or oil on the surface. The bond surface should be sandblasted before applying the adhesive. FRP strips should be slightly hand abraded before bonding. Any residual dust should be cleaned off the bond surfaces immediately using air pressure. It is recommended to use peel-ply strips, where possible, which provide an optimum ready-to-go bond surface.

It is also recommended by Schnerch (2005) to introduce a reverse taper of 10-20° to the end of fibre reinforced polymer strips. This has been shown to cause a significant performance increase in both static and fatigue loading conditions.


2.8 Analysis of Bond Stresses

The stress distribution within the adhesive bond depends on the applied loading pattern, geometry of the bonded system, and the mechanical properties of the adherends and adhesive. Several approximate closed-form solutions have been developed for the interfacial stress in adhesively bonded fibre reinforced polymer strengthened beams (Smith and Teng 2001; Shen et al. 2001; Tounsi and Benyoucef 2007). The main focus of these solutions is rectangular concrete beams strengthened with FRP plates with low flexural stiffness. They all assume linear elastic behaviour for all the materials involved.

Stratford and Cadei (2006) provides a modified elastic closed-form solution for FRP strengthened steel I-section beams. The validity of this approximate closed-form solution is restricted to sufficiently long beams with a continuous adhesive bond between constant cross-section adherends. The authors acknowledge that for more complex geometries such as an intermediate crack or a local defect in the bond, it is necessary to use more complex numerical methods such as finite difference or finite element methods.

For design purposes, the maximum stress in the bond should be limited to the adhesive strength. Stratford and Cadei (2006) recommend not using the manufacturer-reported adhesive strength. These reported strengths are usually based on lap-splice tests done under factory-controlled conditions which are not necessarily representative of the in-situ conditions. The adherends might also not necessarily be the same as those used in practice. More importantly, the reported results are usually the average stress along the bond length of the lap-splice specimen tested. This is far less than the peak stress
developed in the bond. Such a comparison, therefore, is not valid. Instead, it is recommended to use the back-analysis method described in CIRIA-C595 (2004). In this approach, lap-splice tests are conducted using the same materials to be used in-situ. The average failure load found experimentally and the closed form solutions are used to predict the peak shear and tensile (peeling) stress in the bond. The equations provided are based on the work done by Hart-Smith (1973) which assumes all the materials to be isotropic, linear elastic. The peak shear and tensile stress are used to calculate the maximum principal stress in the bond, assuming they occur at the same location. This maximum principal stress, called the “characteristic strength” of the adhesive, was recommended by the authors to be used instead of the manufacturer-reported adhesive strength for design purposes.

There are several drawbacks with this method:

- The average failure load is obtained for real lap-splice tests. The materials involved, particularly adhesive, do not necessarily behave in a linear elastic manner at failure.

- The equations provided by Hart-Smith (1973) assume the adherends to be isotropic which is not true for fibre reinforced material.

- The equation used for double shear lap tests provides the maximum normal stress which is compressive in nature. This might not be representative of the maximum tensile strength of the adhesive.
• Using the maximum principal stress as the failure criterion (Rankine failure criterion) is most suitable for brittle material. Epoxy-type adhesive behaviour is usually brittle. This is not the case, however, for other types of adhesives, e.g. methacrylate-type adhesive, which demonstrate significant ductility.

2.9 Finite Element Modelling

The finite element technique has been used by several researchers to study adhesively bonded FRP systems. Different methods have been used to model the adhesive bond. Defining the adhesive layer as a separate continuum is advantageous since it makes it possible to analyze the stress distribution within the bond layer. Teng et al. (2002), Seleem et al. (2010), and Garcia et al. (2011) used either two-dimensional (2-D) or three-dimensional (3-D) modeling to successfully predict the stress distribution within the bond layer. However, this modelling technique requires the exact mechanical properties of the adhesive material as well as the geometry of the adhesive layer. The effect of characteristics of the adhesive that are difficult to quantify, such as thickness and Poisson’s ratio, was parametrically examined by He (2010).

The adhesive bond can also be modelled using the so-called “bond-slip” equations or by defining a series of springs. Defining such characteristics involves exhaustive experimental work which inevitably requires approximate methods (See for example El-Damatty et al. 2003; Xia and Teng 2005; Ferracuti et al. 2007). Such techniques, in
addition, involve reading strain on the outer surface of fibre reinforced polymer material which is not necessarily representative of the interfacial strains since the fibre reinforced polymer thickness is considerable (e.g. GFRP plates).

2.10 Summary

Premature fatigue failures are a concern for designers of modular bridge expansion joints. Field splices used for modular bridge expansion joint centre-beams are a particular concern.

No literature was found describing the use of FRP to splice steel beams. A solid knowledge of the behaviour of such a hybrid FRP-steel splice is needed to assess the feasibility of this approach. On the other hand, one needs to ensure that the fatigue resistance of such details is adequate.

Previous research on systems consisting of FRP bonded to steel indicates that the adhesive bond is the most important design concern. The available closed-form models for stress analysis within the bond are appropriate for simple cases (isotropic materials, rectangular cross-sections), but may not be suitable for the more complicated geometry of the proposed splice details described in Chapter 1.
2.11 REFERENCES


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CHAPTER 3

ADHESIVE SELECTION

3.1 INTRODUCTION

An experimental research program was conducted to study the role of adhesives on the quality of bond between glass fibre reinforced polymer (GFRP) material and steel. This research program consisted of 17 double shear lap tests [Table 3-1]. The effect of four different parameters on the bond strength, including the adhesive type and bond length, was studied and the results have been discussed in this chapter.

The necessity of such a study was due to the limited knowledge available for the adhesive bond between GFRP and steel, as discussed in detail in Chapter 2. The results will be used later in Chapters 4 and 5 where the behaviour of a new hybrid steel/GFRP splice detail has been investigated.

The double shear lap splice detail was chosen for the purpose of this study. It is believed that from the simple configurations recommended by Cadei et al. (CIRIA C595, 2004) to investigate adhesive bond strength, the double shear lap splice resembles more closely the stress state developed in the zone near the midspan gap of the proposed splice details (Chapter 4). The adhesive layer of a single shear lap splice can develop flexural compressive stresses as a result of the eccentric loading. These stresses are not expected in the adhesive layer of the proposed splice details under the expected applied loads.
Two different adhesive types, namely epoxy and methacrylate, were used in this study. The two adhesives, identified by Schnerch (2005) as having the shortest effective bond length in flexural bending, are investigated. The selection of the adhesives was also based on the work of Hart-Smith (1973), El-Damatty (2003), and Xia and Teng (2005), a full discussion of which is presented in Chapter 2.

A finite element (FE) model for selected test specimens was developed in a commercial finite element package, ABAQUS, to further analyze the stress within the bond in detail and to conduct a parametric study. The model was verified by comparison with experimentally obtained data. This model was also used to propose a method for estimating the strength of adhesively bonded strengthening systems of FRP and steel.

3.2 Experimental program

3.2.1 Materials

GFRP plates were cut from the same pultruded GFRP sections which were used later in making the proposed Splice Detail #1 [Figure 4-1] to ensure consistency of the results. A table-top wet tile saw with a diamond blade was used to cut the plates out of the GFRP tube sections.

These pultruded 103 mm by 103 mm square tube sections, made by Bedford Reinforced Plastics, Inc., are produced with wall thicknesses of 6 or 10 mm. The wall of the 10 mm thick section contains 6 layers of continuous E-glass filament mat (1½ oz; Type M-8643)
with longitudinal, continuous E-glass roving (Type 366-113 (4400 TEX)) in between each layer of mat. Both mat and roving layers are provided by Owens Corning and wetted with isophthalic polyester resin (Type Aropol 2036-C). Polyester surface veils (Nexus 111-10) are provided on either side. The glass fibre volume fraction was 50%. Four layers of mat and 3 layers of roving have been used to pultrude the 6 mm thick section (Fam and Scutezky 2006). Based on manufacturer’s design guidelines, a copy of which is provided in Appendix A for further reference, the ultimate strength and modulus of elasticity in the direction of the fibres, is 206.8 MPa and 17.2 GPa respectively.

Steel plates were made of hot-rolled steel with a nominal yield strength of 350 MPa and nominal modulus of elasticity equal to 200 GPa.

Two adhesives were used. SP systems Spabond 345 is an epoxy-type adhesive made by Gurit (UK) Ltd. The mixing ratio of resin to hardener is 2:1 by volume. A fast hardener was used to reduce the clamping time. The cleavage strength of the cured epoxy is 12.35 kN. This is equal to 33 MPa for tensile strength according to ASTM D 1062-08. The shear strength of the epoxy is 36.6 MPa. The product data sheet is presented in Appendix B for reference. Additional data on the mechanical properties of the adhesive were obtained from Schnerch (2005) who found the stress-strain curve of the adhesive under tensile forces to be linear and elastic up to failure [Figure 3-1]. The tensile modulus of elasticity and Poisson’s ratio of the adhesive was reported to be 3.007 GPa and 0.38 respectively.
Chapter 3  Adhesive Selection

Weld-on SS620 is a methacrylate-type, two-component adhesive made by IPS Structural Adhesives, Inc. The mixing ratio of adhesive (Part A) to activator (Part B; SS605B) is 10:1 (by volume). It has a nominal tensile strength of 18 to 21 MPa and lap shear strength of 19 to 22 MPa, based on the manufacturer’s technical data sheet. The modulus of elasticity of the adhesive is reported to be within a range 413 to 517 MPa. The product data sheet is presented in Appendix C for reference.

3.2.2 Specimen Preparation – Tensile Test Coupons

Tensile coupons were prepared from 10 mm thick GFRP pultruded profiles using the specifications outlined in ASTM D3039/D3039M-08. Six coupons were used, each approximately 300 mm long, 25 mm wide and 10 mm thick. Aluminum tabs, each 90 mm long and 3 mm thick, were adhesively bonded to the end of each coupon. The length of the tabs was calculated based on the estimated ultimate strength of the GFRP material and the shear strength of the adhesive being used (ASTM D3039/D3039M-08; Equation 3).

The dimensions of each coupon were measured as per ASTM D3039/D3039M-08, and the results presented in Table 3-2. Strain gauges were mounted at mid-length of each coupon. Two of the specimens had strain gauges mounted on both sides to check for bending of the samples.
3.2.3 Specimen Preparation – Double Shear Lap Splice Specimens

For each lap splice specimen, two steel plates, sandblasted on each side using the grit specifications as suggested by Schnerch et al. (2007) [Table 3-3], were aligned longitudinally using wood blocks [Figure 3-2]. The bond area on the steel plates was marked and the grip area covered by duct tape to ensure it remained clean. The longitudinal centreline of both steel and GFRP plates were also marked [Figure 3-3].

A second bond surface preparation method, henceforth called the “enhanced” method, was used for some specimens in which more contact area has been provide between the bond surfaces. Before sand blasting the surface of the steel plates, narrow X-shape notches (less than 2 mm deep) were created on the surface using a hand grinder as shown in Figure 3-4. The surface was then sandblasted. In the next step, the steel bond surface was washed off by acetone and dried using air pressure.

The GFRP bond surface was prepared differently in the afore-mentioned two preparation methods. In the “typical” method, the FRP surface was slightly hand-abraded using a #100 sand paper as recommended by Schnerch et al. (2007). In the “enhanced” method, the GFRP bond surface was sandblasted using the same grit specifications as for the steel plates [Figure 3-5]. The dust was cleaned from the GFRP plate surface using air pressure. It was then washed off by isopropanol 99% and dried using air pressure.

The adhesive was applied uniformly to both surfaces. In order to avoid any air voids trapped in the bond, the adhesive was applied in a triangular form so that more adhesive was on the centreline. Using a roller, a constant pressure was applied to the GFRP plate
from the centre of the specimen to its corners to force any trapped air to exit from between the adherents. E-glass spacer beads of 0.8 mm diameter were applied to the bond surfaces to ensure a consistent bond thickness as per Schnerch et al. (2007) [Figure 3-6]. The GFRP plates were held in place for the minimum required setting time of the adhesive. Then, the wood blocks were removed and more adhesive was applied to the edges in a fillet form [Figure 3-7].

The specimen was left in place for a minimum of 24 hours in the lab environment before the same procedure was done for the other side of the specimen. When epoxy-type adhesive was used, the specimen was cured at 50°C for a minimum of 16 hours to reach its nominal strength in a short span of time, as advised by the manufacturer. A minimum of 24 hours at the lab temperature, on the other hand, was sufficient for the methacrylate-type adhesive to reach its nominal strength as stated by the manufacturer.

**3.2.4 Test Procedure – Tensile Coupon Tests**

Tensile coupon tests were conducted according to ASTM D3039/D3039M-08. All coupons were tested using a 250 kN MTS testing machine. Load was applied using stroke control at a rate of 2 mm/min. Figure 3-8 illustrates a typical sample being tested. Load, stroke, and mid-length strain were recorded. The MTS testing machine was equipped with fully automatic hydraulic wedge grips. The data acquisition system was Hottinger-Baldwin-Messtechnik (HBM) BL12A.
3.2.5 Test Procedure – Double Shear Lap Splice Tests

The experimental program consisted of seventeen (17) double shear lap splice specimens. Table 3-1 is a summary of the test matrix. Three bond lengths, two different types of adhesive, two preparation methods for the bond surfaces, and two thicknesses of the GFRP plate were examined.

Figure 3-9 is a schematic of the specimen used in this experiment. Two steel plates, each 70 mm wide by 12 mm thick were joined using two GFRP plates, each 50 mm wide by 10 mm or 6 mm thick. A 10 mm gap between steel plates was provided. Three different bond lengths, namely 95, 195 and 445 mm, were examined.

The intention in designing the specimens was to vary the bond length so that three failure modes would be observed: (1) GFRP rupture, (2) delamination of GFRP plate, and (3) debonding through the adhesive layer. The design was based on the strength of the GFRP plates using the mechanical properties provided by the manufacturer.

All specimens were tested using a 250 kN Instron testing machine. Load was applied using stroke control at a rate of 0.3 mm/min. The Instron testing machine was equipped with fully automatic hydraulic wedge grips. The data acquisition system was Vishay Micro-Measurements System 5000 Model 5100B Scanner.

One strain gauge, mounted at the mid-length of the specimen, was used to read the maximum strain in GFRP at failure. Load, stroke, and mid-length strain were recorded. More strain gauges were mounted to the GFRP surface for selected specimens to measure
the strain change along the longitudinal axis of the specimen. The strain gauges were mounted at different distances from the specimen mid-length as illustrated in Figure 3-10.

### 3.2.6 Test results and discussion – Tensile Coupon Tests

The results for the coupon tensile tests are illustrated in Figure 3-11. The recorded ultimate load and strain, and calculated ultimate strength and elastic modulus are summarized in Table 3-2.

According to the results, the GFRP material had a mean modulus of elasticity and ultimate strength in the direction of fibres equal to 21.5 GPa and 405 MPa, respectively. The mean ultimate strain was 1.9%. The results for modulus of elasticity and ultimate strength are 24% and 96% higher than the nominal properties provided by the manufacturer. Although the test was done using coupons from the 10-mm thick GFRP section, both the 6-mm and 10-mm thick FRP sections were assumed to have similar mechanical properties.

### 3.2.7 Test results and discussion – Double Shear Lap Splice Tests

Table 3-1 summarizes the ultimate strengths for the lap splice tests. Figure 3-12 is a comparison of the average bond strengths for the two adhesives tested. The average value for each bond length is shown by dots, whereas dashes show the range of data used to take each average. For the 445 mm bond length, for which epoxy was used, only one test result was determined. This explains why there is no range for this case. Because of limited number of experimental data for each case, scatter in data is shown by “range”
rather than the standard deviation. Note that specimen S-11 (Bond length: 445 mm; Adhesive: methacrylate) did not fail during the test, because it reached the capacity of the testing machine. In order to calculate the average bond strength, the ultimate capacity of the testing machine (250 kN) was taken as the lower bound of the ultimate capacity for this case. Specimens S-1 and S-4 were not included in the results because they used FRP plates with different thickness. The effect of all other parameters was neglected in this comparison.

For each bond length, the methacrylate-type adhesive was stronger on average than the epoxy-type adhesive. The strength of the epoxy-type adhesive samples did not increase, within the scatter of the test results, with increase in bond length. There is, on average, an increase in the bond strength of the methacrylate-type adhesive with an increase of bond length from 95 mm to 195 mm. This implies a greater effective bond length for the methacrylate-type adhesive.

Figure 3-13 shows the typical load-strain response for the lap-splice tests, for the case of a bond length of 195 mm. The methacrylate-type adhesive demonstrates a smoother and more ductile behaviour. In particular, the methacrylate-type adhesive did not exhibit premature cracks which are evident as flat line segments around 30-50 kN. These segments were associated with a loud snapping sound heard during the testing.

The effect of using an enhanced preparation method versus a typical one for bond surfaces is shown in Figure 3-14. There are limited data for comparison of the two
surface treatments; however, on average the specimens with the enhanced treatment have bond strengths 15% to 43% stronger than the typical treatment.

The effect of FRP plate thickness is shown in Figure 3-15 for a bond length of 195 mm. Again, there are limited data for the comparison. However, for both adhesives, a thinner plate resulted in a strength that was 50% to 100% less than the thicker plate.

Two failure modes for the bond between FRP and steel substrate were observed:

- Debonding of the FRP plate through the epoxy layer [Figure 3-16 a]
- Delamination of the FRP plate through a layer of fibres close to the steel substrate [Figure 3-16 b].

The failure path in both cases occurred in the form of a U- or S-shape, without any particular bias [Figures 3-17 a and b]. Although the samples were designed to include the possibility of a third failure mode, i.e. rupture of the FRP plates, this failure mode was not observed in any of the samples. Tensile coupon tests were conducted, as earlier mentioned, to derive the actual mechanical properties of the GFRP material. The results for modulus of elasticity and ultimate strength are 24% and 96% higher than the nominal properties provided by the manufacturer. This explains why the third failure mode was not observed. It can also be seen in Figure 3-13 that the maximum strain recorded in the GFRP was well below its average failure strain of 1.9 %, providing further evidence that failure was not due to rupture of the FRP.
The delamination failure mode was mainly observed for samples with the methacrylate-type adhesive. This, in line with higher strengths attained for these samples, implies that a stronger bond between steel and GFRP is achievable using the methacrylate-type adhesive. The debonding failure mode, observed for samples with the epoxy-type adhesive, typically occurred at the adhesive-to-steel interface. This implies a weaker bond between the epoxy-type adhesive and steel.

Appendix D provides a more detailed discussion of all the results, including the stress-strain curves for all the samples tested, for further reference.

Figures 3-18 to 3-23 show the strain variation along the longitudinal axis on the exterior side of the GFRP plate with load, $P$, increase. Figures 3-18, 3-20, & 3-22 show the results for specimens made with the epoxy-type adhesive for the bond lengths 95, 195, and 445 mm respectively. The results for the specimens made with the methacrylate-type adhesive are shown in Figures 3-19, 3-21, & 3-23.

For the epoxy-type adhesive, there is a region within about 20 mm of the mid-length in which the maximum strains occur, and the strain is generally uniform (although this is not the case for the 445 mm bond length). Beyond this region, the strain reduces. Beyond a distance about 100 to 120 mm from the mid-length, the strain is essentially constant at any applied load. This implies that the load transfer from GFRP to steel plate has occurred by this length.

For the methacrylate-type adhesive at a bond length of 95 mm, the behaviour is similar to that observed for the epoxy, namely large strains within a 20 mm region, followed by a
reduction. At a bond length of 195, there is a region of large strains over a 40 mm region, and then a reduction in strain beyond this length. At the 445 mm bond length, the trend is for the strain to reduce within about 100 mm to 150 mm up to a load of 100 kN. At higher loads, the strains reduce over much longer lengths (300 mm to 400 mm). The reason for this observation is the ability of the methacrylate-type adhesive to yield. This will be discussed more in the modelling section.

The strain distribution along the longitudinal axis at a particular level of loading (120 kN) is almost the same for different bond lengths for the epoxy-type adhesive [Figure 3-24]. For the methacrylate-type adhesive, however, an upward shift from a bond length 95 mm to 195 mm was observed. The strain distribution is similar for bond lengths 195 and 445 mm [Figure 3-25]. This experimental observation, which implies a higher effective bond length for the methacrylate-type adhesive, is used later when modeling the splice. Only a splice with a bond length of 195 mm was modeled, to reduce computational time.

A comparison between the results shows that the strain is more uniformly distributed along the longitudinal axis for the methacrylate-type adhesive. At a given load level, more strain is developed in the GFRP plate for this type of adhesive. This observation can be attributed to the ability of the methacrylate-type adhesive to yield, a fact verified later by the modelling results. This results in higher bond strengths for specimens with the methacrylate-type adhesive.
3.3 MODELLING

3.3.1 Model Description

A commercial finite element package, ABAQUS, was employed to develop a three-dimensional (3-D), nonlinear model for the double shear lap splice specimens tested.

Steel was modelled as an elasto-plastic material with a tri-linear stress-strain curve as shown in Figure 3-26. This curve is based on the mechanical properties, obtained by Howard 2006, for the I-section steel beams used in this research. Nevertheless, its use can be justified since it is the same grade of steel used for the current tests, and the same mill provided both batches of steel. A parametric study [Figure 3-27] also shows that the dependency of the results on the exact mechanical properties of the steel is negligible.

GFRP was modelled as an orthotropic material. The modulus of elasticity in the direction of fibres ($E_t$) was taken equal to 21.5 GPa as per the results from coupon tests. The modulus of elasticity in the direction perpendicular to the fibres ($E_p$) was taken equal to 5.5 GPa as per the manufacturer data sheet. The GFRP cross section perpendicular to the direction of fibres can be assumed as a plane of isotropy. A value of 0.3 was taken for the Poisson’s ratio in this plane ($\nu_p$). Compared to the isotropic state, there is less resistance against the lateral change in volume when the load is applied in the direction of fibres. Thus, in the absence of experimental results, the Poisson’s ratio for this direction, $\nu_{tp}$, was assumed arbitrarily 0.45 which is greater than $\nu_p$=0.3. The relation between $\nu_{tp}$ and $\nu_p$ is:

$$\nu_{pt} = \left( \frac{\nu_{tp}}{E_t} \right) \times E_p \quad (3 - 1)$$
Thus, $\nu_{pt} = 0.12$.

Since the plane perpendicular to the direction of fibres was assumed as a plane of isotropy, the conventional relation between $G_p$, $E_p$, and $\nu_p$ was used to calculate $G_p$. The shear modulus of elasticity in the plane of isotropy, $G_p$, was thus calculated to be equal to 2.1 GPa. The manufacturer data sheet provided a $G$ value equal to 3.1 GPa, however, it is not clear from the information provided the direction to which it pertains. In the absence of any experimental data and considering the greater value for the reported $G$, it was assumed that $G_t = 3.1$ GPa. The derivation of the elements of the compliance matrix, as defined in the ABAQUS user manual, is straightforward.

The adhesive layer can be either modelled as a continuum or a cohesive surface. The traction-separation laws (alternatively called the “bond-slip” model) required to model the adhesives as a cohesive surface were unknown. It was decided, thus, to model the adhesive layer as a continuum because the required material properties to develop this model are better known than those required for a bond-slip model. The epoxy-type adhesive was modelled as a linear-elastic continuum layer using the mechanical properties obtained by Schnerch (2005) [Figure 3-1]. The methacrylate-type adhesive was modelled as an elasto-plastic material. A tri-linear stress-strain curve [Figure 3-28] was used for this purpose. This curve is based on the results of a typical tensile test performed on the adhesive, provided by the manufacturer to the author (Appendix E). Poisson’s ratio was assumed to be 0.4. This is assuming that the adhesive properties are in the rubber-to-glass transition region (He 2010).
Due to symmetry, only one quarter of the specimen was modelled. Adequate constraints on the steel plates’ surface were introduced to simulate the gripped area. A distributed tensile load was applied to the one end, while the other end was constrained against all the six degrees of freedom [Figure 3-29].

A combination of mesh refinement and submodelling techniques were employed to obtain the exact value of the strain at the points of interest [Figure 3-30]. The area of interest was isolated and re-meshed using finer mesh sizes in successive steps. The boundary condition required to drive each successive sub-model was imported from the parent model which is termed the “global model”. Strain was read as the limit of the average of the corresponding values read in all integration points of the elements adjacent to point of interest in the successive steps of submodelling.

The end tip of the epoxy layer, where there is a re-entrant corner, is a point of singularity. In practice there is likely local damage in these regions which will reduce these stresses. As such, and to avoid the complexity of other methods, the stress at a distance 2 mm from the end was studied instead (Teng et al. 2002).

Convergence of the results was studied using the equation below. Mathematically stated, submodelling continued until:

\[ S_{n+1} - S_n < 1 \text{ MPa (or} \ 0.001 \varepsilon \) \] 

(3 - 2)

where \( S_n \) is the result obtained in the \( n^{th} \) step of submodelling.
Quadratic hexahedral elements (C3D20R) were used in most cases unless the geometry of the problem required using tetrahedral elements (C3D10M). In a mesh refinement process, three conditions are necessary to ensure a convergence of the results (Desai and Abel 1972). One of the requirements is to make sure that all the previous meshes are contained within the finer mesh at any stage of mesh refinement. Hexahedral elements are better options compared to tetrahedral elements to meet this condition. Moreover, compared to the tetrahedral elements, they are reported to provide a solution of equivalent accuracy at less cost (ABAQUS user manual). The reduced integration method was used as it reduces the running time by almost one-fourth. There is no “hourglassing” problem for the C3D20R elements as per ABAQUS user manual. On the contrary, fully integrated elements may suffer from “locking” behaviour. A modified version of the tetrahedral element (C3D10M) was used where necessary. Regular tetrahedral elements are not appropriate for hard contact problems. Hybrid elements were avoided as recommended by ABAQUS user manual. These elements are only beneficial for almost incompressible materials (\(\nu > 0.48\)).

3.3.2 Results and Discussion

As explained above, there are uncertainties in the mechanical properties assumed for the steel and methacrylate adhesive. The effect of unknown mechanical properties of the materials involved was investigated in a parametric study.

First, values for Poisson’s ratio for the methacrylate adhesive ranging between 0.1 and 0.45 were examined. The load versus mid-length strain curves corresponding to different
values for the Poisson’s ratio of the adhesive have been compared in Figure 3-31. The results show negligible dependency on the exact value for Poisson’s ratio. The dependency of the results on the mechanical properties of steel was also studied and already shown in Figure 3-27. Two stress-strain curves were used for steel: (1) a bilinear elasto-plastic curve as per nominal mechanical properties, (2) a tri-linear elasto-pastic curve (based on Howard 2006) as illustrated in Figure 3-26. The results show almost no change in the strain developed on the GFRP surface under the applied load. These results indicate that despite having little data on Poisson’s ratio for the adhesive, and limited experimental data for the material properties of the steel, average values for these parameters should be sufficient to model the lap splices.

Figure 3-32 compares the predicted versus experimentally measured strain along the longitudinal axis of the double-shear lap specimens made with the epoxy-type adhesive for the bond length equal to 195 mm. A similar comparison for the specimens made with the methacrylate-type adhesive is illustrated in Figure 3-33. There is, in general, good agreement between the results predicted by the finite element model and the experimentally measured values for both adhesive types. The results are more consistent for the epoxy adhesive. Nevertheless, the discrepancy between the results is less than 25%, making it an acceptable model as per NCHRP Report 402.

The model indicated that the methacrylate adhesive yielded at failure. This explains why there is a longer load transfer length for the specimens made with this type of adhesive.
The model was used to study the effect of GFRP thickness. The maximum principal stress developed in the epoxy-type adhesive layer was about 30% higher for the case of a 6 mm thick GFRP plate. This explains why lower failure loads were obtained for the specimens made with the 6-mm thick GFRP plates.

3.4 Strength Prediction for Adhesives

Generally, different failure criteria are proposed depending on material behaviour. The Rankine failure criterion (based on the maximum principal stress), is most suitable for brittle materials such as epoxy-type adhesives. Methacrylate adhesive, in contrast, has significant ductility. The von-Mises criterion or maximum shear strain (Hart-Smith 1973) is more appropriate for methacrylate adhesive.

Representative shear lap splice tests have been suggested by other researchers as a means to characterise the strength of adhesives (CIRIA C595, 2004). Closed-form analytical solutions, provided by Hart-Smith 1973, were used in a “back-analysis” approach proposed by Cadei et al. (CIRIA C595, 2004) to find the strength of adhesives. A detailed discussion of this method and some of its drawbacks was presented in Chapter 2. In brief, the maximum principal stress in the adhesive layer is analytically found for the average experimental failure load obtained from representative shear lap splices. This “characteristic stress” is used as a failure criterion for other FRP/steel adhesively bonded
systems. Such a system is assumed to fail when the maximum principal stress in the bond, found analytically or numerically, exceeds the characteristic stress.

The non-linear finite element model was used to find the maximum stress or strain in the adhesives at the average failure load of the lap splice tests used in this experimental study. These values are taken as the “characteristic stress” and “characteristic strain” of the epoxy- and methacrylate-type adhesives respectively. This is based on the failure criterion most appropriate for each material. A comparison is made between the results obtained using the finite element model described in this chapter and the values obtained using the Hart-Smith (1973) equations as per CIRIA C595 (2004).

For the epoxy-type adhesive, the maximum principal stress in the adhesive layer of the lap-splice specimen at the average failure load was predicted using the finite element model. This stress is termed the “characteristic stress” of the epoxy-type adhesive. It is hypothesized that the failure capacity of any other adhesively bonded FRP/steel system can be determined as the level of loading when the maximum principal stress in the adhesive layer exceeds the “characteristic stress” of the adhesive. For the methacrylate-type adhesive, the maximum shear strain is used as the failure criterion and is called the “characteristic strain” of the adhesive. Alternatively, and for the sake of consistency in comparison, the von-Mises criterion, a representative of the maximum shear strain energy, is used for the methacrylate-type adhesive. It is assumed that the methacrylate-type adhesive behaves linearly-elasitcally in this case.
To save computational time, only a specimen with a bond length 195 mm was modelled. It was hypothesised that the maximum principal stress (or the maximum shear strain), as the cause of failure, is the same in all bond lengths. A combination of mesh refinement and submodelling techniques was used to find the characteristic stress or strain of the adhesives under study. The mesh size was successively reduced from 5 mm to 0.001 mm. The results for each step are presented in Tables 3-4 to 3-6. The convergence criterion stated before (Eq. 3-2) was used and the results are also shown.

For the lap splice specimens made with the epoxy-type adhesive, the maximum principal stress in the adhesive layer predicted by the model, for the average failure load, is 77 MPa [Table 3-4]. The average failure load (151.5 kN) is calculated based on the results for Specimens S-13, S-14, S-12, and S-10. Only the specimens with an enhanced bond surface preparation and 10-mm thick GFRP plate were included in this average. The standard deviation of the results is equal to 16 kN. It is acknowledged that the number of specimens is not sufficient for a proper statistical analysis and the scatter in the results is significant. Nevertheless, as will be discussed later in Chapter 4, this scatter in the results was observed for all the specimens made with the epoxy-type adhesive. It seems to be a characteristic of the adhesive.

A comparison was made between the maximum predicted stress in the adhesive and the reported adhesive strength. The maximum tensile and shear strengths of the adhesive as reported by the manufacturer are 33 MPa and 36.6 MPa respectively. They are both much lower (≈ 55%) than the predicted stress at failure. There is experimental scatter – both in
lap splice results and the reported shear and tensile strengths. To make a legitimate comparison between the two, one needs to know the scatter in the reported strengths which is not given. On the other hand, the scatter in the lap splice test results is high (coefficient of variation = 11%). Given this scatter, obviously, more strength test data is needed to make a definitive comparison. Nevertheless, the results imply that nominal reported adhesive strengths may not be appropriate for predicting the strength in a splice connection. This observation is in line with reports by other researchers (CIRIA C595, 2004).

On the other hand, the maximum principal strength of the epoxy-type adhesive, as per CIRIA C595, 2004 equations A6.10 to A6.17, is equal to 132 MPa. This strength is 71% higher than the finite element results for the “characteristic strength” of the epoxy-type adhesive (i.e. 77 MPa). As such, it could result in an unconservative design.

Similar considerations hold true for the specimens made with the methacrylate-type adhesive. For the sake of comparison, the characteristic strength of the methacrylate-type adhesive has been derived using von-Mises stress failure criterion instead of maximum shear strain [Table 3-6]. To derive this strength it is assumed that the adhesive acts linearly elastically without any yielding. The average failure load used for this purpose (=194 kN) is based on the results for Specimens S-8, S-9, S-17, S-7, and S-16, the ones with the enhanced bond surface preparation and a 10-mm thick GFRP. Specimen S-11 was excluded from this calculation since the specimen did not fail. The standard deviation and coefficient of variation are 20 kN and 10% respectively. Again, the number
of the test results is not sufficient for a definitive statistical comparison and the scatter in the results is relatively high. Nevertheless, the following statements can be made.

A comparison between the calculated strength (82 MPa) and the yield strength of the adhesive (20 MPa) clearly shows that the adhesive yields at the level of failure. Thus a comparison between the proposed strength and the nominal strength is not possible. On the other hand, there is no reported nominal shear strain at failure for the methacrylate-type adhesive to compare with the proposed characteristic strain, 0.55 [Table 3-5]. Considering the fact that yielding has occurred in the adhesive at failure, the maximum principal stress failure criterion proposed by Cadei et al. (CIRIA C595, 2004) is not the most pertinent one for this case. Moreover, the adhesive strength predicted using their analytical method (CIRIA C595, 2004 equations A6.10 to A6.17), namely 98 MPa, is lower than the corresponding strength of the epoxy-type adhesive. This implies, misleadingly, that the latter develops stronger bond in practice which is contrary to the observed findings. This could be attributed to the neglected plastic behaviour of the methacrylate-type adhesive. On the other hand, a comparison between the predicted strengths for the two adhesives, using the currently proposed finite element model, shows that, although different failure criteria have been used, the predicted strength for the methacrylate-type adhesive is higher than the epoxy-type adhesive; a result confirmed by experimental findings. The results are summarized in Table 3-7.

The validity of the characteristic strength and strain values for predicting the failure of these adhesives will be examined in Chapter 5. These characteristic attributes of the
adhesives are used later in Chapter 4 to predict the failure capacity of the proposed spliced details. The results are compared to the experimental ones.

### 3.5 CONCLUSIONS

#### 3.5.1 Conclusions from Experimental Work

The following conclusions could be drawn from the experimental work:

- An “enhanced” preparation method for bond surfaces creates a stronger bond between adherends. This preparation method is thus recommended to be used instead of the typical one suggested by Schnerch et al. 2007.

- Despite its lower nominal strength and higher effective bond length, a stronger bond between steel and GFRP is achievable using the methacrylate-type adhesive. Reported nominal strengths might be unrealistic and sometimes misleading.

- The results show that the load transfers from GFRP to steel plate within 100 – 120 mm of the bond length for the case the epoxy-type adhesive is used. This could be taken as the effective bond length for this adhesive.

- The methacrylate-type adhesive causes the load to transfer from GFRP to steel within longer bond lengths due to its plastic behaviour.
• The adhesive bond system using the methacrylate-type adhesive is more ductile due to the ability of the adhesive to yield.

• Double shear lap tests should be an exact resemblance of the FRP application in practice. Experimental results show that changing mechanical and geometric parameters have a significant influence in the final results.

• The epoxy-type adhesive develops a weaker bond with the steel than the GFRP.

3.5.2 Conclusions from Modelling

From the modelling results, it is concluded that:

• In order to obtain the characteristic strengths of different adhesives, it is proposed to conduct a series of shear lap splice tests, which accurately resemble the intended specific application, in conjunction with an appropriate non-linear finite element analysis. The maximum value for each attribute, found numerically for the level of loading equal to that of average failure load obtained experimentally, is called the “characteristic strength” of the adhesive and will be used to predict failure of other adhesively bonded systems.

• Different characteristic attributes should be used for different adhesives. Maximum principal stress, for the brittle epoxy-type adhesive and maximum shear strain for the ductile methacrylate-type adhesive (or equivalently von-Mises stress) seem to be adequate attributes.
• Nominal strengths of the adhesives, reported by the manufacturer, should not be used for the purpose of adhesive bond strength prediction. Not only are they unnecessarily conservative, but also sometimes misleading.

• The proposed method by Cadei et al. (CIRIA C595, 2004) does not seem to be accurate. The results were shown to be unconservative in this study.
3.6 REFERENCES


### Table 3-1- Double-lap splice test matrix

<table>
<thead>
<tr>
<th>Adhesive</th>
<th>Bond length (mm)</th>
<th>Specimen</th>
<th>Other parameters</th>
<th>Ultimate capacity (kN)</th>
<th>Failure shape</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy</td>
<td>95</td>
<td>S-13</td>
<td>Enhanced</td>
<td>10</td>
<td>126</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S-14</td>
<td>Enhanced</td>
<td>10</td>
<td>157</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>195</td>
<td>S-1</td>
<td>Typical</td>
<td>6</td>
<td>76</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S-2</td>
<td>Typical</td>
<td>10</td>
<td>148</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S-12</td>
<td>Enhanced</td>
<td>10</td>
<td>170</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S-15†</td>
<td>Enhanced</td>
<td>10</td>
<td>117†</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>445</td>
<td>S-10</td>
<td>Enhanced</td>
<td>10</td>
<td>153</td>
<td>S</td>
</tr>
<tr>
<td>Methacrylate</td>
<td>95</td>
<td>S-8</td>
<td>Enhanced</td>
<td>10</td>
<td>180</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S-9</td>
<td>Enhanced</td>
<td>10</td>
<td>169</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S-17</td>
<td>Enhanced</td>
<td>10</td>
<td>185</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>195</td>
<td>S-3</td>
<td>Typical</td>
<td>10</td>
<td>239</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S-4</td>
<td>Typical</td>
<td>6</td>
<td>161</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S-7</td>
<td>Enhanced</td>
<td>10</td>
<td>222</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>445</td>
<td>S-5</td>
<td>Typical</td>
<td>10</td>
<td>161</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S-6‡</td>
<td>Typical</td>
<td>10</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S-11</td>
<td>Enhanced</td>
<td>10</td>
<td>245</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S-16</td>
<td>Enhanced</td>
<td>10</td>
<td>214</td>
<td>U</td>
</tr>
</tbody>
</table>

* BSPM*: Bond Surface Preparation Method
† S-6: This specimen failed in compression due to an error in testing.
‡ S-11: This specimen did not fail within the capacity of the testing machine.
§ AS: Adhesive-to-Steel interface
¶ AF: Adhesive-to-FRP interface
†† S-15: with no circumferential adhesive fillet
††† Refer to Figure 3-17

### Table 3-2- Tensile coupon test matrix

<table>
<thead>
<tr>
<th>Sample</th>
<th>Width (mm)</th>
<th>Thickness (mm)</th>
<th>Area (mm²)</th>
<th>Failure load (kN)</th>
<th>Ultimate strength (MPa)</th>
<th>Ultimate strain (%)</th>
<th>Modulus of Elasticity (E11) (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured</td>
<td>Average</td>
<td>Measured</td>
<td>Average</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-1</td>
<td>24.6</td>
<td>24.5</td>
<td>9.7</td>
<td>9.6</td>
<td>235</td>
<td>94.1</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>24.5</td>
<td>24.8</td>
<td>8.4</td>
<td>8.3</td>
<td>216</td>
<td>91.0</td>
<td>421</td>
</tr>
<tr>
<td></td>
<td>24.9</td>
<td>24.7</td>
<td>9.7</td>
<td>9.8</td>
<td>215</td>
<td>85.2</td>
<td>396</td>
</tr>
<tr>
<td>C-2</td>
<td>24.6</td>
<td>24.5</td>
<td>9.7</td>
<td>9.6</td>
<td>228</td>
<td>93.8</td>
<td>411</td>
</tr>
<tr>
<td></td>
<td>24.9</td>
<td>24.7</td>
<td>9.8</td>
<td>9.7</td>
<td>241</td>
<td>95.1</td>
<td>395</td>
</tr>
<tr>
<td>C-3</td>
<td>24.6</td>
<td>24.8</td>
<td>9.3</td>
<td>9.2</td>
<td>203</td>
<td>83.0</td>
<td>409</td>
</tr>
<tr>
<td>C-4</td>
<td>24.6</td>
<td>24.8</td>
<td>9.3</td>
<td>9.2</td>
<td>203</td>
<td>83.0</td>
<td>409</td>
</tr>
<tr>
<td>C-5</td>
<td>24.6</td>
<td>24.8</td>
<td>9.6</td>
<td>9.6</td>
<td>203</td>
<td>83.0</td>
<td>409</td>
</tr>
<tr>
<td></td>
<td>24.7</td>
<td>24.8</td>
<td>9.3</td>
<td>9.3</td>
<td>203</td>
<td>83.0</td>
<td>409</td>
</tr>
<tr>
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<td>24.6</td>
<td>24.8</td>
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<td>203</td>
<td>83.0</td>
<td>409</td>
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<tr>
<td>C-6</td>
<td>24.6</td>
<td>24.8</td>
<td>9.3</td>
<td>9.3</td>
<td>203</td>
<td>83.0</td>
<td>409</td>
</tr>
</tbody>
</table>

Mean  | 405 | 1.90 | 21.5 |
SD*** | 9.2 | 0.10 | 0.91 |
CV**** | 0.023 | 0.053 | 0.042 |

* The ultimate strain was not recorded due to premature failure of strain gauge.
** Calculated using data before strain gauge failure.
*** Standard Deviation
**** Coefficient of Variation
Table 3-3- Grit requirements for surface preparation of steel (Adapted from Schnerch et al. 2007)

<table>
<thead>
<tr>
<th>Property</th>
<th>Minimum value</th>
<th>US standard screen</th>
<th>% retained per sieve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>2.65</td>
<td>16</td>
<td>0.4</td>
</tr>
<tr>
<td>Moh’s hardness</td>
<td>6.5</td>
<td>20</td>
<td>11.3</td>
</tr>
<tr>
<td>Shape</td>
<td>angular</td>
<td>30</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40</td>
<td>33.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>8.5</td>
</tr>
<tr>
<td>Pan</td>
<td></td>
<td></td>
<td>2.9</td>
</tr>
</tbody>
</table>

Table 3-4- Characteristic strength of the epoxy-type adhesive

<table>
<thead>
<tr>
<th>Adhesive: Epoxy</th>
<th>Load</th>
<th>Mesh size (mm)</th>
<th>Max principal stress (MPa)</th>
<th>$S_{n+1} - S_n$ (MPa)</th>
<th>Convergence study</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>151.5 kN</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step</td>
<td></td>
<td>Mesh size (mm)</td>
<td>Max principal stress (MPa)</td>
<td>$S_{n+1} - S_n$ (MPa)</td>
<td>Convergence study</td>
</tr>
<tr>
<td>0</td>
<td>5 &amp; 2</td>
<td></td>
<td>43.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td></td>
<td>60.1</td>
<td>16.7</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td></td>
<td>66.4</td>
<td>6.3</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.1</td>
<td></td>
<td>73.2</td>
<td>6.8</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.05</td>
<td></td>
<td>74.7</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.01</td>
<td></td>
<td>76.3</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.005</td>
<td></td>
<td>76.9</td>
<td>0.6</td>
<td>OK</td>
</tr>
<tr>
<td>Limit</td>
<td></td>
<td></td>
<td>77</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3-5- Characteristic strain for the methacrylate-type adhesive

<table>
<thead>
<tr>
<th>Adhesive: Methacrylate</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Load</strong></td>
<td>194 kN</td>
<td>2 mm from gap</td>
<td>Convergence study</td>
</tr>
<tr>
<td><strong>Step</strong></td>
<td>Mesh size (mm)</td>
<td>Maximum shear strain (ε)</td>
<td>$S_{n+1} - S_n$ (ε)</td>
</tr>
<tr>
<td>0</td>
<td>5 &amp; 2</td>
<td>0.368</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0.481</td>
<td>0.113</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>0.511</td>
<td>0.03</td>
</tr>
<tr>
<td>3</td>
<td>0.1</td>
<td>0.539</td>
<td>0.028</td>
</tr>
<tr>
<td>4</td>
<td>0.05</td>
<td>0.545</td>
<td>0.006</td>
</tr>
<tr>
<td>5</td>
<td>0.01</td>
<td>0.547</td>
<td>0.002</td>
</tr>
<tr>
<td>6</td>
<td>0.005</td>
<td>0.548</td>
<td>0.001</td>
</tr>
<tr>
<td>7</td>
<td>0.001</td>
<td>0.549</td>
<td>0.001 OK</td>
</tr>
<tr>
<td><strong>Limit</strong></td>
<td></td>
<td><strong>0.55</strong></td>
<td></td>
</tr>
</tbody>
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Table 3-6- Characteristic strength for the methacrylate-type adhesive

<table>
<thead>
<tr>
<th>Adhesive: Methacrylate</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Load</strong></td>
<td>194 kN</td>
<td></td>
<td>Convergence study</td>
</tr>
<tr>
<td><strong>Step</strong></td>
<td>Mesh size (mm)</td>
<td>von-Mises stress (MPa)</td>
<td>$S_{n+1} - S_n$ (MPa)</td>
</tr>
<tr>
<td>0</td>
<td>5 &amp; 2</td>
<td>74.4</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>78.1</td>
<td>3.7</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>79.8</td>
<td>1.7</td>
</tr>
<tr>
<td>3</td>
<td>0.1</td>
<td>81.4</td>
<td>1.6</td>
</tr>
<tr>
<td>4</td>
<td>0.05</td>
<td>81.6</td>
<td>0.2</td>
</tr>
<tr>
<td>5</td>
<td>0.01</td>
<td>81.8</td>
<td>0.2 OK</td>
</tr>
<tr>
<td><strong>Limit</strong></td>
<td></td>
<td><strong>82</strong></td>
<td></td>
</tr>
</tbody>
</table>
Table 3-7- A comparison between adhesive strength found from different methods

<table>
<thead>
<tr>
<th>Adhesive</th>
<th>Strength (MPa)</th>
<th>Proposed method</th>
<th>Cadei method</th>
<th>Nominal strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy</td>
<td>Maximum principal stress</td>
<td>77</td>
<td>132</td>
<td>36**</td>
</tr>
<tr>
<td>Methacrylate</td>
<td>von-Mises stress</td>
<td>82</td>
<td>98*</td>
<td>21**</td>
</tr>
<tr>
<td></td>
<td>Maximum shear strain</td>
<td>0.55***</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

*Maximum principal stress.
**Greater value of the reported nominal shear and tensile strengths.
***Strain is unitless.
Figure 3-1- Stress-strain curve for the epoxy-type adhesive (Adapted from Schnerch 2005)

Figure 3-2- Using wood blocks to align steel plates
Chapter 3  Adhesive Selection

Figure 3-3- Shear lap splice specimen marked and taped

Figure 3-4- Enhanced preparation method: X-shape notch on steel surface
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Figure 3-5- Enhanced preparation method: GFRP plate sand blasted

Figure 3-6- E-glass beads used to ensure required adhesive thickness
Figure 3-7- Additional adhesive in a circumferential fillet form

Figure 3-8- Typical coupon for GFRP
Figure 3-9- A schematic of the double shear lap specimen – top view

Figure 3-10- Shear-lap splice specimen being tested- Strain gauges mounted along its longitudinal axis
Figure 3-11- Stress-strain curve for GFRP

Figure 3-12- The average strength versus bond length (The average value for each bond length is shown by dots, whereas dashes show the range of data used to take each average.)
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Figure 3-13- Load-strain behaviour; a comparison between adhesive types.

Figure 3-14- Effect of preparation method for bond surfaces
Figure 3-15 Effect of FRP plate thickness

Figure 3-16- Failure modes: (a) debonding; (b) delamination
Figure 3-17 Failure shapes: (a) S-shape; (b) U-shape

Figure 3-18- Strain along longitudinal axis; Epoxy-BL= 95 mm
Figure 3-19- Strain along longitudinal axis; Methacrylate-BL=95 mm

Figure 3-20- Strain along longitudinal axis; Epoxy-BL=195 mm
Figure 3-21- Strain along longitudinal axis; Methacrylate-BL=195 mm

Figure 3-22- Strain along longitudinal axis; Epoxy-BL= 445 mm
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Figure 3-23- Strain along longitudinal axis; Methacrylate-BL=445 mm

Figure 3-24- Strain distribution along the longitudinal axis; a comparison between different bond lengths; Epoxy-type adhesive
Figure 3-25- Strain distribution along the longitudinal axis; a comparison between different bond lengths; Methacrylate-type adhesive

Figure 3-26- Stress-strain curve for steel
Figure 3-27- Dependency of the model results to the exact mechanical properties of steel

Figure 3-28- Stress-strain curve for the methacrylate-type adhesive
Figure 3-29- One-fourth of the shear lap splice specimen modelled using finite element technique; Boundary condition applied

Figure 3-30- C3D20R mesh elements; submodelling technique
Figure 3-31- A parametric study on the effect of Poisson's ratio- Methacrylate-type adhesive

Figure 3-32- A comparison between strain experimentally measured and predicted using model- Epoxy-type adhesive
Figure 3-33- A comparison between strain experimentally measured and predicted using model- Methacrylate-type adhesive
CHAPTER 4

BEHAVIOUR OF THE PROPOSED SPLICE DETAILS UNDER STATIC LOAD- EXPERIMENTAL PHASE

4.1 INTRODUCTION

Two splice details were proposed to meet the unique requirements of modular bridge expansion joints. The main feature of these splice details is that they are hybrid steel/FRP systems. No previous attempt to use FRP to splice beams was found in the literature. Nevertheless, the unique features of FRP, as discussed in Chapter 2, make it a suitable candidate for this purpose.

The first splice detail, inspired by the fish-plate splice detail [Figure 1-5], is comprised of a GFRP pultruded section adhesively bonded to the soffit of the beam. The beam web is spliced using steel plates and bolts [Figure 4-1] while a GFRP pultruded section is used to restore the bending moment resistance of the intact beam. The steel web plates are used to align the beam section. The top surface of a modular bridge expansion joint centre-beam is not accessible and, thus, the moment resistant component of the splice is located in the lower part of the beam. Pultruded FRP sections, commercially available in the market, are only made of GFRP with a limited range of mechanical properties. The one used in this research was the most suitable for the proposed application in terms of mechanical properties.
The second splice detail uses FRP plates adhesively bonded to the top and bottom flanges of the spliced beam to resist the applied moment [Figure 4-2]. Similar to Splice Detail #1, the steel beam is aligned using bolted steel web plates. These plates also carry shear forces, if there is any. Both GFRP and CFRP plates were used in this splice detail.

The main advantage of such splice details is envisaged to be in applications where field welding should be avoided. They are also specifically designed for cases when the top surface of the beam is not accessible. One of these applications is for the centre-beams of modular bridge expansion joints. Other envisaged applications include, but are not limited to, railroads. To examine the suitability of the proposed splice detail for the modular bridge expansion joint centre-beams, a comparison needs to be made between the load and boundary conditions used for the tests in the current study and those typical of a modular bridge expansion joint. The centre-beams in a modular bridge expansion joint typically have spans between 0.8 and 1.4 metres and are continuous over several spans depending on the width of the bridge deck (NCHRP Reports 402 & 467). In the current study, to reduce the complexity of the test set-up, a single span spliced beam was tested.

The behaviour of the hybrid steel/FRP spliced beam, under both serviceability and ultimate limit states, is studied experimentally in this chapter. The main objectives of this experimental study are:
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- To identify the splice detail that has sufficient stiffness and strength to satisfy the requirements of the serviceability and ultimate limit states as mandated for expansion joints in various bridge design codes.
- To obtain data from carefully controlled experiments that would permit validation of a model.

The two adhesives already introduced in Chapter 3 were used in this study. In the beginning, the epoxy-type adhesive was used to make the splices since it was the one recommended by Schnerch et al. (2007). The results were not promising though. This led to the study of the adhesives as described in Chapter 3. The results convinced the author to use the methacrylate-type adhesive in making the splices despite its lower nominal strength. A comparison between the results of the splices made by the two adhesives further supports the results in Chapter 3 that the published nominal strengths were misleading. The specimens made with the methacrylate-type adhesive yielded much more promising results.

4.2 Experimental program

The behaviour of the two proposed hybrid steel/FRP splice details under static loads was examined in an experimental program. In total, seventeen (17) steel beams [Table 4-1], cut from W100 ×19 wide flange I-shaped sections, each 1.2 m long, were loaded under a four-point bending pattern as shown in Figure 4-3. The net span between supports was
1.0 m. The space between point loads was selected to be equal to the centre-to-centre spacing between the two tires of one of the wheels of the CL-625 ON truck load axle. Specimens $A1$ to $A3$ were undamaged and unstrengthened control beams. Specimen $B$, an intact beam strengthened using an adhesively bonded GFRP section [Figure 4-4], served as a control to verify the developed finite element model (Chapter 5). The GFRP section thickness was 6 mm. Specimens $C1$ to $C9$ were cut through entire depth at midspan and spliced using Splice Detail #1 [Figure 4-1]. The GFRP section was adhesively bonded to the soffit of the beam. The web of the steel beam was spliced using 6 mm thick steel plates on each side and fastened with four bolts.

The effect of two different adhesives, two different GFRP section thicknesses, two different methods for the preparation of bond surfaces, three different end shapes, and four different splice lengths were examined. The first three parameters were the epoxy-versus methacrylate-type adhesives, 6 mm versus 10 mm thick GFRP sections, and typical versus an enhanced method of preparing bond surfaces. These parameters are all defined in detail in Chapter 3. The various end shapes used in this experimental parametric study are shown in Figures 4-5 a-e. They were introduced to the end of GFRP section to mitigate the effect of local stress raisers. Various splice length-to-span ratios, ranging from 0.4 to 0.95, were also examined.

Specimens $D1$ to $D4$ were spliced using Splice Detail #2 [Figure 4-2]. Ultra-High Modulus CFRP plates were used in Specimens $D1$ and $D2$. The effect of two different adhesives was examined. GFRP plates were used to splice Specimens $D3$ and $D4$. The
web of the steel beam was spliced in the same way as in Splice Detail # 1. A 45° reverse taper was introduced to the ends of all FRP plates, as recommended by Schnerch et al. (2007), to reduce the local stress concentration at this point. It is noteworthy that Specimen $D_4$ was statically tested after being subjected to one-million cycles of fatigue loading (Chapter 5).

### 4.2.1 Materials

The W100×19 wide flange section was manufactured from Grade 350W (CSA-G40.21) with a nominal yield strength of 350 MPa and modulus of elasticity of 200 GPa. The W100x19 section was selected because it is similar in scale to those used for the center-beams of modular bridge expansion joints.

The bolts were ASTM A325 with a nominal diameter 12.7 mm.

The GFRP section, produced by Bedford Reinforced Plastics, Inc., is pultruded and cut from square tubes with an outer dimension of 103 mm. The GFRP plates were cut from the pultruded sections using a table-top wet tile saw with a diamond blade. A full account of the GFRP material property is presented in Chapter 3.

HM1020 Ultra-High Modulus CFRP plates, made by Mitsubishi Chemical Inc., were examined as an alternative to GFRP plates in Splice Detail #2. These peel-ply FRP plates were pre-cured with a nominal width and thickness of 100 and 2 mm respectively [Figure 4-6]. The mechanical properties of this material were obtained by Howard 2006. The
mean modulus of elasticity and ultimate strength in the direction of fibres are 396 GPa and 1431 MPa respectively.

The two adhesives used in this study, namely SP systems Spabond 345 (epoxy) and Weld-on SS620 (methacrylate) have already been introduced in Chapter 3. A full description of their mechanical properties is presented there.

4.2.2 Fabrication of Test Specimens

For each beam, holes were drilled in the web to accommodate the bolts. The outer surface of the beam flange which contacts the FRP was then sandblasted. Grit specifications recommended by Schnerch et al. (2007) were used for this purpose (Table 3-3). Narrow x-shape notches (less than 2 mm deep) were introduced to the surface prior and in addition to the sandblasting in the enhanced preparation method (Figure 4-7a).

Next, the beam was cut into half using a band saw machine. The two halves were then re-assembled using bolted web plates (Figure 4-7b). The average gap between the ends was 3 mm. The bolts for all specimens, except for Specimen C1, were then pretensioned using the turn-of-the-nut method (CAN/CSA-S16-01). After snug-tight installation, the nuts were rotated an additional ⅓ turn (Figure 4-7c). The required torque (∼110 N·m) was later checked using a torque wrench. For Specimen C1, they were pretensioned using a torque wrench. The torque applied was 110 N·m.

Splice lengths (i.e. GFRP section length) ranging between 400 and 950 mm, for Splice Detail #1, were examined. This was equal to a splice length-to-span ratio range from 0.4
to almost 1. A splice length of 400 mm is based in part on tests of Spabond 345 which indicate that the development length for this epoxy is 76 mm to 102 mm when used to bond CFRP to steel (Schnerch 2005). If these results are applicable for GFRP, the development length provided in the proposed detail is approximately twice the minimum development length. The development length, however, was taken here as the length from the midspan gap which acts as an intermediate crack.

Only one splice length, i.e. 950 mm, was used for the Splice Detail #2. This was the maximum practical length for FRP plates (equal to a splice length-to-span ratio of almost 1).

The length of the web steel plates remained constant in all specimens (400 mm) to restrict the number of parameters involved.

Immediately before applying the adhesive, the GFRP surface was abraded slightly using #100 sandpaper. In the case of the enhanced preparation method it was sandblasted using the same grit specifications used for the steel surface (Figure 4-7d). The dust was then removed using air pressure and further cleaned using isopropanol 99%. The already sandblasted steel surface was cleaned with acetone.

The bond surface area was then marked and isolated from the rest of steel beam using duct tape. Then, the resin and hardener of adhesive were mixed, according to the published recommendations of the manufacturer, using a special gun, and applied to both surfaces of GFRP and steel. In order to avoid any air voids trapped in the bond, the adhesive was applied uniformly in a triangular form so that more adhesive was on the
centreline. Using a roller, a constant pressure was applied to the GFRP from centre of specimen to its corners to force any trapped air to exit from between the adherends. E-glass spacer beads of 0.8 mm diameters were applied to the bond surfaces to ensure a consistent, optimum bond thickness as per Schnerch et al. (2007). The epoxy thickness was targeted at 1 to 2 mm. The two surfaces were placed on top of each other and clamped for 24 hours. The extra epoxy coming out of the corners was cleaned. For the epoxy-type adhesive, the specimen was cured at 50 ºC for a minimum of 16 hours to reach its nominal strength in a short span of time, as advised by the manufacturer. A minimum 24 hours at the lab temperature, on the other hand, was sufficient for the methacrylate-type adhesive to reach its nominal strength as stated by the manufacturer [Figure 4-8].

For Specimen C4, the ends of the specimen were cut with a radius of 100 mm to reduce the stress concentrations at this location (Figures 4-1 and 4-5c). This radius was chosen to create a smooth increase in cross section from tangent to the steel flange surface. The cut was done by a milling machine. As a result, some layers of glass fibres at the ends were either cut or debonded from the resin matrix they were initially embedded. The experimental results showed that this did not cause a significant loss in the integrity of the section.

For Specimens C8 and C9, the ends of specimen were cut in a 45° angle as shown in Figure 4-5b. In addition the end of section at its interface with adhesive was inversely tapered at 45° angle to mitigate the local stress concentration as recommended by
Schnerch et al (2007). This was done using a diamond blade saw. This modified shape is an intermediate between the radius (Figure 4-5c) and right angle (Figure 4-5a) end shapes. It is easier to cut and at a lower cost than the radius cut.

For the specimens made using Splice Detail #2, the reverse taper at the end was created using a diamond blade saw for GFRP plate (Figure 4-5d) and a band sanding machine for Ultra-High Modulus CFRP plate (Figure 4-5e). No major defects, other than those mentioned, were observed as a result of introducing the above-mentioned end shapes.

4.2.3 Test Set-up and Instrumentation

All specimens were tested using a 1,000 kN Riehle universal testing machine (Figure 4-9a). Load was applied using stroke control at a rate of 1 mm/min. A LM60-900K load cell was used in these experiments with a relative error ± 1%. Semi-cylindrical bearings at the ends (Figure 4-9b) and a spherical bearing at the load point (Figure 4-9c) were used to ensure simply supported load conditions. An extra steel beam was used between the load shaft and the specimen to divide the applied load into two point loads (Figure 4-9a). Elastomeric pads were used between the beam and the spherical bearing to mitigate the effect of possible misalignments (Figures 4-9b and 4-9c).

Up to 6 linear potentiometers (LPs) (Figure 4-10) and 24 strain gauges (Figures 4-11 and 4-12) were used to conduct a detailed study of the behaviour of the spliced beams under the applied loading. Strain gauges were also mounted on the FRP, web splice plates, and on the steel beam.
Novotechnik TRS 100 and TRS 25 LPs were used in this study. According to the manufacturer data sheet (Appendix F), their independent linearity is ± 0.075% and ±0.2% respectively. Accordingly, recording data with a precision of 0.1 mm was achievable. The LPs were calibrated before each test using a micrometer.

C2A-06-250LW-120 Vishay strain gauges were used. Their respective strain range, according to the manufacturer data sheet (Appendix G), is ± 3% within a temperature range -50°C to +80°C. The instructions given in Appendix H were followed in order to align and mount the gauges.

The data acquisition system was Vishay Micro-Measurements System 5000 Model 5100B Scanner with a resolution 1 µε. The data was recorded at a rate 1 scan/second. During the tests, a shunt calibration error less than 5% was taken as acceptable. Considering the given relative error for gauge factor (0.5%) and the uncertainty regarding the other sources of error, this (5%) could be taken as the combined relative error of strain gauges and data acquisition. It should be mentioned that Vishay Company did not comment on an inquiry made in this regard.

4.2.4 Loading Regimes

Specimen A1 was loaded up to failure [Figure 4-13], while Specimens A2 and A3 were loaded and unloaded in their elastic range up to ≈ 50 kN to compare the modulus of elasticity [Figure 4-14]. Specimen B was loaded, in the elastic range, up to ≈ 70 kN to investigate the hybrid behaviour of the system under serviceability limit states [Figure 4-
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15]. It was also used to compare the strengthening effect of GFRP section by comparing the resultant modulus of elasticity to that of control beam.

Specimen C1 was put under four cycles of loading/unloading up to 80 kN [Figure 4-16]. Specimen C2 was first loaded up to 30 kN. At this point, it experienced two cycles of loading/unloading before being loaded up to 50 kN, another two cycles of loading/unloading at this level and finally loading up to failure as illustrated in Figure 4-17. This was mainly done to observe the post-crack behaviour of the splice.

Specimen C3, a replicate of Specimen C2, was loaded directly up to failure to compare the failure capacity.

Specimen C4 had a loading regime similar to that of Specimen C2 except that cycles of loading/unloading happened at 20 kN and 40 kN respectively [Figure 4-18]. Again, this was done to assess the post-crack behaviour of the specimen.

Specimens C5 and C6 were loaded up to failure. Specimen C7 experienced several cycles of loading/unloading at different levels of loading, before and after cracks, to further check the post-crack behaviour of the spliced beam [Figure 4-19].

The rest of the specimens, namely C8, C9, D1, D2, and D3 were loaded directly up to failure. Specimen D4 was subjected to 1,000,000 cycles of fatigue loading at a rate 0.6 Hz before being statically loaded up to failure. This was done to assess post-fatigue behaviour of the specimen.
4.3 Results and Discussion

The results of the experiments are presented in Figures 4-13 to 4-40. The slope of the linear portion of each load-deflection plot, as well as the recorded ultimate load, is presented in Table 4-1. Note that, for some tests, the response was only measured in the linear-elastic region, and the specimens were not loaded to failure. For these tests, the ultimate load was not measured and is indicated in Table 1 as N/A (i.e. not applicable).

The tests on the control beams will be discussed first. This will be followed by tests on strengthened beam, Splice Detail #1, and then Splice Detail #2.

4.3.1 Load-Deflection Response of Control Beams

Specimen A1 served as a control beam. Figure 4-13 illustrates the load-midspan deflection curve of the specimen loaded up to failure. The test ended due to the local buckling in the top flange under the point loads. The midspan deflection was an average of deflection measured on both back and front sides of the beam. The flexural stiffness and ultimate capacity of the intact beam were 44.5 kN/mm and 269 kN respectively. Two further intact beams (Specimens A2 & A3) were loaded in their elastic range (up to ≈ 50 kN). The flexural stiffness of the specimens was 48.8 kN/mm and 43.3 kN/mm respectively [Figure 4-14].

4.3.2 Results for Strengthened Beam

The strengthened beam (Specimen B) was loaded, in the elastic range, up to ≈ 70 kN to investigate the hybrid behaviour of the system under serviceability limit states. The load-
deflection response is illustrated in Figure 4-15. The flexural stiffness of the strengthened beam is 47 kN/mm. A comparison between Specimen A1 and B shows negligible increase (< 5%) in the stiffness as a result of strengthening. This is mainly due to the significantly lower flexural stiffness of the GFRP section compared to the steel beam (≈ 6%) and the shear lag effect as will be discussed in the following.

The strain distribution for Specimen B at the midspan cross-section at various levels of loading is shown in Figure 4-20. The vertical axis in this figure shows the cross-sectional distance (mm) from FRP-to-steel interface. The results show that there is a shear lag effect for the FRP section and the strain does not vary linearly throughout the cross section even at midspan.

The strains measured immediately above and below the interface at midspan are almost the same. The shear lag effect is due to the FRP section. Even if the adhesive bond is not perfect and there is a change in strain over the interface due to the shear lag in the adhesive, theoretically this should not be seen at midspan due to symmetry. It was expected to see a linear change in the strain immediately over the interface at this point. A further inspection showed that the strain gauges on the FRP section were installed about 3 mm off the centre line. This might explain why the strain did not change linearly over the adhesive layer at midspan.

The results for the two strain gauges installed immediately above and below the interface at a distance 100 mm from midspan show an increase in the strain over the interface [Figure 4-21]. This figure shows the difference in the strain measured on the two sides of
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GFRP/steel interface versus the applied load. The strain in steel is greater than that in FRP and this difference in the strain linearly increases by the increase in the applied load. This implies a progressive shear distortion in the adhesive layer.

4.3.3 Results for Splice Detail 1

4.3.3.1 Load-Deflection Response of GFRP Splices with Square Ends

Figure 4-16 shows the load-deflection response for a beam spliced with a 6 mm thick GFRP section (Specimen C1) for four successive cycles of loading/unloading. In the first cycle, the beam exhibited linear behaviour up to 12 kN loading. At this point, cracking of the epoxy at the end corner tips of the FRP section was observed [Figure 4-22]. The beam was unloaded after reaching an applied load of 80 kN. There was a residual deflection of 2 mm after unloading which can be attributed to slippage of the bolted web plates because the bolts were pretensioned using a torque wrench. The slippage occurred at 30 kN. For the other spliced beams, the bolts were installed using the “turn-of-the-nut” installation procedure. The response with subsequent load cycles was consistent, and exhibited elastic behaviour with a pronounced hysteresis. It could be seen that the flexural stiffness did not change significantly as a result of slip in the steel web plate. At 65 kN, the beam appeared to stiffen. This can be attributed to the gap in the steel beam closing at the splice location.

Specimens C2 and C3 were made using 10 mm thick GFRP sections. For Specimen C2, the first snapping sounds were heard at about 20 kN which could be attributed to internal
cracks. However, visible cracks were observed in the epoxy at the end corner tips of the FRP section at about 45 kN (Figure 4-17). Slip of the steel web plates occurred at a higher load level, 55 kN, compared to Specimen C1. This was attributed to the implementation of the more reliable “turn-of-the-nut” pretensioning method for this specimen. Cracks in epoxy widened, and the spliced beam failed at 70 kN with a sudden rupture of the epoxy (debonding). Several load cycles were applied at different load levels to see the post-crack behaviour of the spliced beam. Despite residual deflection, which could be attributed to the lower flexural stiffness of the beam as a result of cracks at the bond line, the load-deflection behaviour of the beam remained linear elastic in successive load cycles and the formed cracks did not show a progressive increase in length at this stage.

First cracks in the bond occurred at around 30 kN for Specimen C3 and the specimen failed at 45 kN (Figure 4-23). The failure mode was similar to Specimen C2, namely a sudden adhesive bond failure starting from one end.

The load-midspan responses of Specimens C1, C2, and C3, in its linear regime up to the first visible cracks, are compared in Figure 4-24. The load-midspan curve for Specimen C1 is taken from the second loading cycle. This illustrates the effect of FRP thickness. All specimens had similar end shapes (right angle) and splice length (400 mm). Similar bond surface treatments (typical) were used. Specimen C1 was made using a 6-mm thick GFRP section, whereas the other two used a 10 mm thick GFRP section. Specimen C2 had almost the same flexural stiffness as Specimen C3. Comparing Specimens C2 and C3
to $C_1$, an increase in the GFRP thickness by 67% resulted in an increase in flexural stiffness of only 20%.

The ultimate capacity of the spliced beam, on the other hand, decreased despite having a GFRP section with a larger thickness. Specimen $C_2$ failed at 45 kN and $C_3$ failed at 70 kN. Specimen $C_1$ was not loaded to failure. However, it is clear that its capacity is significantly larger than $C_2$ and $C_3$ despite having a smaller GFRP thickness. It is believed that larger stresses should have been developed at the end of box section for Specimens $C_2$ and $C_3$, as compared to Specimen $C_1$, due to the thicker section and increased stiffness. Subsequent analysis using the finite element model (Chapter 5), however, indicates that the maximum principal stress in the adhesive layer in the region close to the end corner tips of FRP section is larger for Specimen $C_1$ by 33%. Nevertheless, the region with high stress is more spread in Specimen $C_2$. The number of specimens tested is not statistically significant and there is a scatter in the strength of the epoxy–type adhesive as explained in Chapter 3. More research is required to specify the specimen with higher strength and the reason for it.

Specimens $C_2$ and $C_3$ were replicate specimen of each other. However, there was a wide range in the observed ultimate strengths: 45 kN for Specimen $C_3$ to 70 kN for Specimen $C_2$. Given that both failed by adhesive bond failure, one reason for the scatter in strength could be the wide scatter in epoxy bond strengths as reported in Chapter 3.

In an attempt to improve the strength of Splice Detail #1, longer lengths of bonded GFRP were investigated. Figure 4-25 compares the load-midspan deflection for Specimens $C_2$, $C_3$, and $C_1$.
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C5, C6, and C7. The specimens had GFRP lengths of 400, 500, 700 and 950 mm respectively. They all had the same end shape (right angle). Similar adhesive (epoxy) and surface treatment (typical) were used in their manufacture.

The first crack in Specimen C5 was observed at about 20 kN. It was followed by a premature debonding failure at about 40 kN. No crack was observed in Specimen C6 up to ≈ 50 kN. The stiffening behaviour could be attributed to the smaller gap at midspan. The steel plates did not yield for this case.

The full load-deflection curve for Specimen C7 is illustrated in Figure 4-19. Initial cracks formed at ≈ 40 kN and propagated towards midspan from one end. At about 80 kN, cracks from both ends started to propagate towards midspan. This resulted in significant midspan deflection as illustrated in Figure 4-19. This caused the end tips of the upper flange to come together which restored part of the stiffness. No slip was noticed for the web steel plates. They experienced significant yielding. Several cycles of loading/unloading were performed at the levels of loading 30 kN, 50 kN, and 80 kN. The results provide further evidence that the post-crack behaviour of the spliced beam under a constant load level remains linear elastic.

The results for the flexural stiffness and ultimate strength of the specimens are presented in Table 4-1. The flexural stiffness of Specimens C2, C5, C6, and C7 are compared in Figure 4-26. The results show a linear increase in the elastic flexural stiffness as the splice length increases from 400 to 950 mm. However, a linear trend in the ultimate capacity was not observed. Subsequent analysis using the finite element model, presented
later in Chapter 5, indicates that the strength of the specimens should be increased as the FRP length increases assuming the maximum principal stress in the adhesive is the sole failure criterion.

One reason for the unexpected results could be related to the failure mode, which was adhesive bond failure in each case. As reported in Chapter 3, there is wide scatter in bond strengths. This was observed with Specimens C2 and C3, which had a wide range in strength despite being replicate specimens. Given this scatter, it is not clear if the trend observed in Figure 4-26 is statistically significant without further tests.

### 4.3.3.2 Load-Deflection Response of GFRP Splices with Modified Ends and Surface Treatment, and Different Adhesive

The tests of Specimens C1, C2, C3, C5, C6, and C7 all showed evidence of cracks occurring in the epoxy at loads well below the expected ultimate capacity of the splice. These cracks reduced the stiffness of the splice and likely its capacity. One reason postulated for these cracks is the large stress raiser that could be expected at the geometry change at the square end of the GFRP section where it is bonded to the steel beam. A common method for reducing such stress raisers is to modify the geometry and increase the radius at the re-entrant corner.

Specimen C4 was modified to reduce the stress concentration at the ends of the GFRP section by introducing a radius end shape [Figure 4-5c]. The load versus midspan deflection is shown in Figure 4-27. No premature cracks in the epoxy at the GFRP ends were observed. Slip between the web steel plates and steel beam web initiated at about
40 kN and continued further up to 50 kN when a sudden debonding of FRP caused the beam to fail.

Figure 4-28 compares the load-deflection response of Specimens C2 and C3 to C4. All three specimens have a GFRP length of 400 mm and epoxy adhesive. All three specimens had similar flexural stiffness, indicating that there was no reduction in the flexural stiffness of the spliced beam as a result of the radius end shape. However, within the scatter of the data, there was no clear improvement in the ultimate capacity.

In a further attempt to improve Splice Detail #1, Specimen C8 had the enhanced surface preparation described in the Experimental Procedure section. This included notching the surface to improve the bond between FRP, steel, and the adhesive. In addition, the end of the GFRP section was cut at a 45° angle as shown in Figure 4-5b to reduce the stress concentration without the cost required to make a radius cut. Specimens C7 and C8 can be compared as both have an identical GFRP bond length (950 mm) and adhesive (epoxy).

Load-deflection curves for the two specimens are compared in Figure 4-29. A slightly lower stiffness was observed for Specimen C8 (~8%). Slip in the steel plates occurred at almost the same load for both specimens and they had similar post-slip behaviour. The major difference is the increase (24%) in ultimate capacity for Specimen C8 as compared to Specimen C7.

Epoxy adhesive was used for specimens C1 to C8 while a methacrylate-type adhesive was used for Specimen C9. Specimens C8 and C9 were similar otherwise. A comparison
between the load-deflection response of the two specimens [Figure 4-30] shows that using the methacrylate-adhesive resulted in higher ductility ($\approx 20\%$, based on maximum deflection at failure) and higher failure capacity (34%). Again, this is consistent with the findings of Chapter 3, which indicated that the methacrylate adhesive had higher strengths in a steel-GFRP lap splice than a comparable epoxy adhesive. Note that despite the promising results for Specimen $C9$ as compared to Specimens $C1$ to $C8$, its stiffness and strength still fall about 18% and 33%, respectively, below an intact steel beam [Table 4-1].

4.3.3.3 Comparison of Failure Modes

In Specimens $C1$ to $C7$, the observed failure mode was a sudden rupture of epoxy [Figure 4-31]. It was hard to capture by the naked eye the initiation point for the debonding. However, premature cracks were always noticed first at the ends of the GFRP section. The GFRP section debonded from the half of the beam in most cases causing significant deformation as a result of a plastic hinge formed at midspan. A combination of yield and slip in the steel web plates was observed at failure for all specimens and the top flange tips came into contact [Figure 4-32]. Specimen $C1$ did not experience yielding in the web steel plates as a result of bolts not being adequately pretensioned. As well, no yield in the web steel plates was observed for Specimen $C6$.

The failure mode for Specimen $C8$ was a combination of FRP delamination (delamination through FRP thickness) at the ends followed by sudden debonding through adhesive layer in the middle. This could be attributed to the enhanced bond surface
preparation method used. The FRP section separated completely as a result of debonding through adhesive layer started from one end [Figure 4-33].

FRP delamination was the sole failure mode observed in Specimen C9. This is in line with the conclusion made in Chapter 3 that the methacrylate-type adhesive, compared to the epoxy-type adhesive, develops a stronger bond with steel. The FRP section did not separate from steel beam [Figure 4-34].

The first visible end crack was observed at 53 kN and 145 kN, respectively, for Specimens C8 and C9. This occurred at a higher load level compared to other specimens where the first crack occurred within a loading range of 30 to 40 kN. This is believed to be due to the smaller stress concentration as a result of the modified end shape. A loud snapping sound was heard for both specimens at around 60 kN which could be attributed to the onset of slip in the steel web plates as well as possible internal cracks in the adhesive layer.

4.3.3.4 Strain Distributions

Typical strains measured over the depth of the cross-section at midspan are presented for Specimens C2 and C7 in Figure 4-35. The strains are shown for an applied load 40 kN in the first loading cycle. Both specimens showed elastic behaviour up to this load. These specimens had splice lengths 400 and 950 mm, respectively. They were similar otherwise. The results show that for a short splice length, strain varies linearly through the steel section up to the top layer of FRP section, which is expected as discussed earlier.
for Specimen B. However, a significant shear lag occurs in the GFRP section. In the long splice length, though, steel and FRP act as a composite section and, within the scatter of data, strain varies linearly along the cross section at midspan. This explains why more flexural stiffness can be achieved by increasing the splice length.

4.3.4 Results for Splice Detail 2

The results for Splice Detail #1 indicated that it would be difficult to design a spliced beam with a stiffness and capacity comparable to that of an intact steel beam. Attention was then turned to Splice Detail #2.

Specimens D1 to D4 were made using Splice Detail # 2. The two parameters studied for this splice detail were FRP material and adhesive type. Specimens D1 and D2 were made using Ultra-High Modulus CFRP plates. The epoxy-type adhesive was identified by Schnerch et al. (2007) as the best adhesive for this material. However the better results obtained for the methacrylate-type adhesive in previous steps encouraged the author to compare the two adhesives for this material as well. Specimen D1 was made using the epoxy-type adhesive whereas the methacrylate-type adhesive was used in Specimen D2. They had similar splice lengths (950 mm) and bond surface treatments (enhanced). Figure 4-36 compares the load-deflection curves for Specimens D1 and D2. There was almost no difference in flexural stiffness. However, Specimen D2, made with methacrylate-type adhesive, showed significantly higher ultimate capacity (53 %) and ductility (200 %). This means that methacrylate-type adhesive had superior performance and created a stronger bond. This could be attributed to its higher ultimate shear strain
capacity as already discussed in Chapter 3. The ultimate strains measured in the CFRP plate adhesively bonded to the soffit of the beam were 3300 µε and 4400 µε for Specimens $D1$ and $D2$ respectively. Specimen $D1$ failed as result of debonding at one end corner followed by a longitudinal split in the FRP plate propagated towards midspan and a final rupture of FRP at midspan [Figure 4-37]. No crack or debonding observed for Specimen $D2$ on the other hand. The specimen failed as a result of FRP rupture at midspan [Figure 4-38]. The ultimate strain developed in the Ultra-High Modulus CFRP plate was 25% higher than the mean value obtained experimentally by Howard (2006), i.e. 3526 µε.

The effect of FRP material was investigated for Splice Detail #2 in a comparison between Specimens $D2$ and $D3$. Specimen $D2$ was made using Ultra-High Modulus CFRP plates whereas GFRP plates were used in Specimen $D3$. The methacrylate-type adhesive was used in both specimens. They had similar splice lengths (950 mm) and bond surface treatments (enhanced). The failure mode for Specimen $D3$ was an intermediate crack delamination. Cracks initiated close to the midspan gap at around 170 kN and propagated toward one end as the load increased. The maximum strain in the GFRP plate at midspan was 16000 µε at around 230kN. The strain gauge failed at that point. Specimen $D3$ failed shortly after at 238 kN.

The load-midspan deflection responses of the Specimens $D2$ and $D3$ are compared in Figure 4-39. There is a slightly lower (8%) ultimate capacity for the case GFRP plates
used. The decrease in flexural stiffness is significant though (≈ 35%). The ductility was larger by 30%.

Specimen $D4$ was statically tested up to failure after being subjected to one-million cycles of fatigue loading as will be discussed later (Chapter 6). Unfortunately the System 5000 data acquisition system failed to save the recorded data at the end of experiment. However, some limited hand-recorded data shows almost no change in its static behaviour after being exposed to one million cycles of fatigue loading. The hand recorded data are as follows. The load deflection curve was linear up to 125 kN where the slope changed in overall behaviour similar to that for specimen $D3$. The failure happened at 287 kN with the same failure mode, i.e. intermediate crack delamination. The maximum strain measured at GFRP at failure was 15500 $\mu\varepsilon$. Unfortunately, the strain or deflection at the point there was a change in the curve slope was not recorded. However, considering the other data, there is slight probability that the initial flexural stiffness or ductility of Specimen $D4$ has been changed significantly with respect to Specimen $D3$.

### 4.3.5 Promising details

Modular bridge expansion joints are designed to resist the wheel loads of a design truck. Fatigue is usually the critical limit state. The governing wheel loads for the Canadian Highway Bridge Design Code, for example, are 87.5 kN (CHBDC 2006 - Cl. 3.8.4.3 & Cl. A3.4.1). In addition, a dynamic amplification of 50% is typical for both the serviceability limit state (SLS) and the ultimate limit state (ULS) (CHBDC 2006 - Cl. 3.8.4.1 & Cl. 3.8.4.5.3). To design for the fatigue limit state (FLS), the traffic load
“should be one truck only, placed at the centre of one travelled lane”. This is not a requirement for SLS and ULS. However, “the truck clearance envelope shall not project beyond the edge of a design lane” (CHBDC 2006 - CL. 3.8.4.1). A typical 5 span centre-beam, with 1 metre long spans, includes a traffic lane (3 metres wide) and two 1 metre wide sides. The splice is assumed to be at the midspan of the second bay such that it will be subjected to positive moments only. The afore-mentioned loads would result in a maximum moment of 10.9 and 8.4 kN·m at the splice, for SLS and FLS respectively [Figure 4-40]. To compare these design loads to the results of the current study, a total load of 73 kN and 56 kN would be needed, respectively, for the test set-up used (single span, span length 1 metre, 4 point bending), as shown in Figure 4-3, to obtain these moments.

Figure 4-41 compares the load-deflection response for the spliced beams with best results, namely C9, D2, and D3 to that of the control beam (A1). As illustrated, the most promising results belong to Specimens D2 and D3. Specimen D2 was able to almost restore both stiffness and strength of the intact beam. This is the most desirable case. The required fatigue loading, as mentioned above, is about 56 kN. The load-deflection curve, for Specimen D2, was linear up to 200 kN. This suggests the potential for very good fatigue resistance under the required fatigue loading. The only drawback was limited ductility. The failure mode was sudden with almost no warning in advance which is not desirable in practice. Specimen D3 overcomes this problem at the expense of lower flexural stiffness. It restored almost 90% of the ultimate capacity of the intact beam. The maximum deflection at failure (a measure of ductility) was almost the same as that of the
control beam. Its flexural stiffness was about 65% of the intact beam. Specimen C9 would rank last in terms of performance compared to the intact beam. It was able to restore the flexural stiffness of the intact beam. However, the ultimate strength and ductility decreased by almost 25% and 70% respectively compared to Specimen A1.

The first visible cracks in the adhesive layer, for Specimen C9, were not observed until 145 kN. However, the first snapping sound was heard at about 60 kN. This might be indicative of internal cracks in the adhesive, which could have the potential to initiate fatigue cracks. More experimental work, however, is needed to verify this statement.

4.4 CONCLUSIONS

Two hybrid FRP/steel splice details have been proposed. Their behaviour under static loads has been experimentally investigated. The effect of several parameters has been studied. Their potential to be used as the field splice for modular bridge expansion joint centre-beams has been discussed.

The following conclusions could be drawn from the experimental work:

- Splice Detail #2 showed a superior behaviour under static loads. This could be attributed to the lower flexural stiffness of the FRP plates compared to the FRP sections used in Splice detail #1.
Chapter 4  Behaviour of the proposed splice details under static load- Experimental phase

- Splice Detail #2, in case a methacrylate-type adhesive was used, is the best candidate for modular bridge expansion joint centre-beam field splices.

- For Splice Detail #2, using GFRP plates resulted in a failure mode with advanced warning. This is more desirable in practice, although, the stiffness and strength reduced compared to the case CFRP plates were used.

- Methacrylate-type adhesive provided a stronger bond between FRP and steel. Its superior ductility, compared to epoxy, also prevented the premature cracks from forming.

- An “enhanced” preparation method for bond surfaces between FRP and steel, as explained in Chapter 3, resulted in superior bond quality and a more consistency in results. It is, thus, recommended for such applications.

- For Splice Detail #1, only part of the FRP section is effective due to the shear lag effect. This allows introducing modified end shapes to eliminate the premature cracks at end tips with negligible change in stiffness.

- Adhesive bond is not sufficient for Splice Detail # 1. Premature cracks due to significant flexural stiffness of the section do not allow taking advantage of the theoretical strength capacity of the splice.

- The post-crack load-deflection behaviour of the spliced beam remained linear and repetitive under a constant applied load. This implies that the cracks are not progressive under a constant applied load.
• For Splice Detail #1, slip occurred between web steel plates and steel beam at around 50-60 kN. Slip occurred at a lower load level if the bolts were not pretensioned. The post-slip and pre-slip stiffness of the spliced beam was almost the same.

• For Splice Detail #1, increasing GFRP section thickness resulted in an increase in the flexural stiffness of the spliced beam. The proportion was not similar though. This could be attributed to the shear lag effect.

• For Splice Detail #1, the flexural stiffness of the spliced beam was linearly proportional to the GFRP section length.
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4.5 REFERENCES


CHBDC. (2006). *CAN/CSA-S6-06, Canadian Highway Bridge Design Code*, Canadian Standards Association (CSA), Mississauga, ON, Canada


### Table 4-1- Test matrix

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Type</th>
<th>FRP</th>
<th>Adhesive</th>
<th>Surface preparation method</th>
<th>Flexural stiffness (kN/mm)</th>
<th>Ultimate strength (kN)</th>
</tr>
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<tbody>
<tr>
<td>A1</td>
<td>Intact Control</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>44.5</td>
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<tr>
<td>A2</td>
<td>Intact Control</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>48.8</td>
</tr>
<tr>
<td>A3</td>
<td>Intact Control</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>43.3</td>
</tr>
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<td>B</td>
<td>Intact Strengthened</td>
<td>GFRP box</td>
<td>400</td>
<td>6</td>
<td>Square</td>
<td>Epoxy</td>
</tr>
<tr>
<td>C1</td>
<td>Splice detail #1</td>
<td>GFRP box</td>
<td>400</td>
<td>10</td>
<td>Square</td>
<td>Epoxy</td>
</tr>
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<td>C2</td>
<td>Splice detail #1</td>
<td>GFRP box</td>
<td>400</td>
<td>10</td>
<td>Square</td>
<td>Epoxy</td>
</tr>
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<td>Splice detail #1</td>
<td>GFRP box</td>
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<td>10</td>
<td>Square</td>
<td>Epoxy</td>
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<td>Splice detail #1</td>
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<td>Square</td>
<td>Epoxy</td>
</tr>
<tr>
<td>C6</td>
<td>Splice detail #1</td>
<td>GFRP box</td>
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<td>10</td>
<td>Square</td>
<td>Epoxy</td>
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<tr>
<td>C7</td>
<td>Splice detail #1</td>
<td>GFRP box</td>
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<td>10</td>
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<td>Epoxy</td>
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<td>C8</td>
<td>Splice detail #1</td>
<td>GFRP box</td>
<td>950</td>
<td>10</td>
<td>45°</td>
<td>Epoxy</td>
</tr>
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<td>C9</td>
<td>Splice detail #2</td>
<td>GFRP box</td>
<td>950</td>
<td>10</td>
<td>45°</td>
<td>Methacrylate</td>
</tr>
<tr>
<td>D1</td>
<td>Splice detail #2</td>
<td>UHMCFRP plate</td>
<td>950</td>
<td>2</td>
<td>45°</td>
<td>Methacrylate</td>
</tr>
<tr>
<td>D2</td>
<td>Splice detail #2</td>
<td>UHMCFRP plate</td>
<td>950</td>
<td>2</td>
<td>45°</td>
<td>Methacrylate</td>
</tr>
<tr>
<td>D3</td>
<td>Splice detail #2</td>
<td>GFRP plate</td>
<td>950</td>
<td>10</td>
<td>45°</td>
<td>Methacrylate</td>
</tr>
<tr>
<td>D4*</td>
<td></td>
<td>GFRP plate</td>
<td>950</td>
<td>10</td>
<td>45°</td>
<td>Methacrylate</td>
</tr>
</tbody>
</table>

* Hand recorded
Chapter 4  Behaviour of the proposed splice details under static load- Experimental phase

Figure 4-1- Splice detail #1

Figure 4-2- Splice detail #2
Chapter 4  Behaviour of the proposed splice details under static load- Experimental phase

Figure 4-3- Loading pattern

Figure 4-4- Strengthened beam (Specimen B)
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Figure 4-5- Various end shapes used for the FRP part

Figure 4-6- HMCFRP plate (peel ply)
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Behaviour of the proposed splice details under static load- Experimental phase

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(d) GFRP surface sandblasted

Figure 4-8- Snapshots from installation process
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Figure 4-9- Test set-up

Figure 4-10- Test set-up: Lay-out for the LPs
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Figure 4-11- General lay-out for strain gauges

Figure 4-12- Lay-out for strain gauges (Specimen B)
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Figure 4-14- Specimens A2 & A3; Load-midspan deflection
Figure 4-15- Specimen B- Load-midspan deflection

Figure 4-16- Specimen C1- Load-midspan deflection
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Figure 4-17- Specimen C2- Load-midspan deflection

Figure 4-18- Specimen C4- Load-midspan deflection
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Figure 4-19- Specimen C7- Load-midspan deflection

Figure 4-20- Specimen B- Strain distribution throughout the depth of cross section at midspan
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Figure 4-22- Specimen C1- Cracks at the end tip
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![Graph showing load-midspan deflection for Specimen C3 with linear regression equations: $y = 18.7x + 1.25$ with $R^2 = 0.9994$ and $y = 22.2x + 0.90$ with $R^2 = 0.9987$.]

Figure 4-23- Load-midspan deflection; Specimen C3

![Graph comparing the flexural stiffness of Specimens C1 to C3 with linear regression equations: $y = 18.7x + 1.25$ with $R^2 = 0.9994$, $y = 22.2x + 0.90$ with $R^2 = 0.9987$.]

Figure 4-24- A comparison between the flexural stiffness of Specimens C1-3 (linear portion)
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Figure 4-26- The effect of splice length on flexural stiffness; Splice detail #1
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Figure 4-35- The effect of splice length on the strain distribution along midspan cross section (Specimen C2 (BL= 400 mm) versus Specimen S7 (BL= 950 mm)); P = 40 kN

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Figure 4-37- Failure mode for Specimen D1: (a) side view; (b) view from underneath

Figure 4-38- Failure mode for Specimen D2
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![Graph](image)

**Figure 4-39- Load-midspan deflection; Specimens D2 & D3**

![Diagram](image)

**Figure 4-40- The design truck location (SLS)**
Figure 4-41 - Load-midspan deflection; a comparison between the best splice details
Chapter 5

BEHAVIOUR OF THE PROPOSED SPLICE DETAILS UNDER STATIC LOAD- MODELLING

5.1 INTRODUCTION

The complicated mechanics of a steel beam spliced using adhesively bonded FRP and bolted web steel plates requires finite element modeling to capture the overall load-deflection response.

A three-dimensional (3-D), non-linear finite element model was developed for the splice details tested in the experiments previously described. The objective was to compare the behaviour predicted by the model to that measured experimentally to verify the model.

Such a model, once verified, can be used to conduct a detailed stress analysis to make an initial statement on which of the splice details is likely to satisfy fatigue limit states as mandated in various bridge design codes.

5.2 MODEL DESCRIPTION

A commercial finite element package, ABAQUS, was used to develop a three-dimensional (3-D), non-linear finite element model for the splice details tested (Chapter 4). Nonlinearities due to both materials and contact were taken into account.
Load was applied as a surface pressure over two narrow rectangles each 103 mm × 10 mm. The beam supports were modeled as a hinge and a roller.

Steel was modelled as an elasto-plastic material with the tri-linear stress-strain curve shown in Figure 3-26. This was based on the experimentally obtained results by Howard 2006.

The GFRP section was modelled as an orthotropic material as described in Chapter 3. The mechanical properties for GFRP in the direction of fibres were obtained experimentally as explained in Chapter 3. It was assumed that both 6 mm and 10 mm thick sections had similar properties. This was based on the manufacturer data sheet which does not differentiate between the two.

Ultra-High Modulus CFRP plate was modelled as an isotropic, linear-elastic material due to lack of required data. The mean modulus of elasticity and ultimate strength in the direction of fibres are 396 GPa and 1431 MPa respectively (Howard 2006).

The adhesive layer was modelled as a 2 mm thick continuum. This was the average thickness of the adhesive layer achieved in experiments. Material properties experimentally obtained by Schnerch (2005) were used for the epoxy-type adhesive [Figure 3-1]. A tri-linear stress-strain curve [Figure 3-28] was used for the methacrylate-type adhesive. This was based on the experimental results reported by the manufacturer (Appendix E). Poisson’s ratio was assumed to be 0.4 as explained in Chapter 4.
The interface between the three materials (FRP, Adhesive, and steel) was modelled as a no-slip contact.

The web plate bolt connection, for the spliced beams, was modelled as circle areas with no-slip contact. Friction contact between steel web plate and steel beam web was introduced in the remainder of the area. The static fiction coefficient was taken as 0.33 (CAN/CSA S16-01). The pretension force in bolts was modelled as an equivalent constant pressure applied to the outer lateral surface of web steel plates from both sides. The pretension force in each bolt, 53 kN, was taken from Table 7- CAN/CSA S16-01. The pressure applied was 8.83 MPa (= [4×53000] / [400*60]).

A gap of 3 mm between the two segments of the spliced beam was modeled. This gap distance was the average of that in the experiments. The nonlinearity due to the closure in the gap at the top flange was modelled as an interaction in load step. Two surfaces, which come into contact under loading, were defined as master and slave surfaces respectively. A surface-to-surface contact with a “hard” contact normal behaviour was defined for this interaction. A sensitivity analysis of the model to the gap size was conducted. In practice, it is better to ignore the additional strength due to gap closure since there will be hardly any control on the size of gap.

The GFRP section (plate) end shape was modelled as in practice. The additional adhesive applied to the ends in a fillet form was also modelled where applicable (Specimens C8 and C9).
A combination of sub-modelling techniques and mesh refinement, as explained in detail in Chapter 3, were adopted. The same convergence criteria were used.

A detailed discussion on the subject of element types, from a theoretical point of view, is provided in Chapter 3. C3D10M elements were adopted generally except where the simple geometry allowed for C3D20R elements (e.g. Specimens A1 and B).

5.3 Verification Methodology

In order to verify the model and the techniques used, a two-step verification methodology was adopted to verify the model and the techniques used in the two simplest cases, namely a simple intact beam and an intact beam adhesively bonded to a FRP section.

First, the intact beam as a control, as shown in Figure 5-1, was modelled. The predicted load deflection response was compared to the experimental results. This helped to verify the material properties used for steel. A sensitivity study of both element type and mesh size was also conducted using this simple model.

Next, a strengthened beam was modelled [Figure 5-2]. The predicted load-midspan deflection of the strengthened beam was compared to the experimental results. This helped to examine the capability of the techniques and material properties in modelling the composite behaviour of steel and FRP.

The verified model, then, was used to model all the specimens experimentally tested as Splice Detail #1 and Splice Detail #2 (Chapter 4). A comparison between the model and
experiment for the load-deflection response of all specimens was conducted to further verify the model. Relatively coarse mesh sizes were required as per the results obtained in the mesh-sensitivity study above-mentioned.

The strain distribution over the depth of the cross section was also compared between the model and experiment. Mesh refinement techniques are required to obtain accurate results for stress or strains. To save in computational effort, only selected specimens, namely Specimens B, C2, and C7, were used for this purpose.

Stress distribution in the adhesive layer was studied, using the model to investigate the areas prone to cracking, i.e. areas with the highest stress level. This was compared, qualitatively, with experimental observations.

The developed model was then used, according to the method proposed in Chapter 3, to predict the strength of spliced beams. The mesh refinement technique was used to find the maximum principal stress or shear strain in splices made with the epoxy-type or methacrylate-type adhesive at a nominal applied load P. This was, next, used to predict the strength by comparing to the characteristic stress (strain) of the adhesives used. It is hypothesised, in this method, that the principal stress (shear strain) is linearly proportional to the applied load. Strength prediction was only done for selected specimens, namely Specimens C8, C9, D1, D2, and D3, due to the computational effort required. These specimens were selected as they exhibited the most promising behaviour in the experimental phase (Chapter 4). Maximum stress in other parts (steel and FRP) was also compared to the strength of each corresponding material.
5.4 RESULTS AND DISCUSSION

5.4.1 Model verification for Intact Beam

A comparison between the predicted load-deflection response for the intact beam (Specimen A1) and the experimental results is illustrated in Figure 5-3. There is in general very good agreement between the results. This is better illustrated if the predicted load-deflection curve is shifted to the right by 0.5 mm. This discrepancy in the initial response can be attributed to the effect of the elastomeric pads that were used in the experiments.

5.4.1.1 Mesh Sensitivity Analysis

The sensitivity of the load-deflection response to the mesh size is shown in Figure 5-4. Hexahedron elements with two sizes, namely 10mm and 5 mm, were used. This comparison was performed at constant loading steps, up to 250 kN, to save in modelling expense. This load range includes part of the nonlinear behaviour. The results show that using relatively coarse elements does not have any adverse effect on the predicted deflection.

Figure 5-5 illustrates the sensitivity of the load-deflection curve to the mesh type. Hexahedron and tetrahedron elements with the same size (10 mm) were used. The results here show almost no dependency on the two mesh types being used, namely quadratic tetrahedral (C3D10M) and hexahedral (C3D20R) elements. The decision on mesh type
selection remains mainly on which element shape fits better with the geometry of the splice detail.

5.4.2 Model Verification for Strengthened Beam

Specimen B was modelled using C3D20R elements. Figure 5-6 compares the predicted versus experimental load midspan deflection for this specimen. The model is approximately 8% stiffer. This is a good comparison given the lack of detailed data on the adhesive and GFRP.

The experimental versus modelling results for the strain distribution along midspan cross section for Specimen B are compared in Figure 5-7. There is in general good agreement between the results. The model predicts an almost linear change of strain over the steel-to-FRP interface, while experimentally it appears there is a large slip occurring as the strain in the GFRP is much lower than the steel. However, as already explained in Chapter 4, the strain gauges on the FRP side were mounted slightly off the centreline, which explains this discrepancy.

These results show that a 3-D, non-linear model using finite element technique, with the adhesive layer being introduced as a continuum, is able to adequately predict the behaviour of adhesively bonded FRP–steel systems.

5.4.2.1 Mesh Sensitivity Analysis

The sensitivity of the results for load-deflection response to the mesh size is shown in Figure 5-8. The results show no dependency even for the case of composite strengthened
beam. As a result, a coarse mesh can be used confidently to obtain load-deflection curves from finite element models. The sensitivity of the results to the exact thickness of the adhesive layer is shown in Figure 5-9. The load-deflection curve shows negligible dependency on the exact thickness of adhesive layer within the range 1 mm to 2 mm.

5.4.3 Model Verification for Splice Detail #1

5.4.3.1 Load-Deflection Comparison

Comparisons between the predicted and experimentally obtained load-deflection response for the spliced specimens, namely Specimens C2, C4, C5, C6, C7, C8, and C9, are illustrated in Figures 5-10 to 5-17. The modelling results were obtained using a relatively coarse mesh as indicated before.

The results for Specimens C2 (Figures 5-10) show a good agreement between the model and experiment up to the point first cracks happened (≈ 20 kN). The discrepancy between the results is about 20%. There is a progressive cracking in the adhesive, after this point, leading to a reduction in the stiffness of the beam, and increasing difference with the model predictions.

The model is not able to predict the post-crack response of the beam. This is not surprising, as no damage criteria was defined for the adhesive layer. A rigorous experimental plan is required to obtain such criteria for each adhesive material to be incorporated into finite element models (Garcia et al. 2011). Other modelling techniques, such as cohesive surface based models, might be able to capture this behaviour. This
requires, though, obtaining several required adhesive properties through extensive experimental tests as explained in Chapter 3.

The model is also incapable of predicting slip of the web steel plates and the post-slip response of the beam. This is probably because the model still has the full effect of the adhesive (no cracking) and at this higher stiffness slip of the plates does not occur. It is noteworthy though, as illustrated Figure 5-10, the experimental post-slip average flexural stiffness is more or less equal to the pre-slip stiffness for Specimen $C_2$. For the purpose of comparison, a special case where there is no contact between web steel plates and steel beam other than bolts was investigated. The model still predicted a response stiffer than the experimental response [Figure 5-10], providing further evidence that the difference between the predicted and experimental response is related to the adhesive cracking. The manufacturer provided nominal mechanical properties for the FRP section and reports its flexural modulus as 12.4 GPa [Appendix A] which is far less than the tensile modulus found by the author experimentally. To investigate this effect, the FRP was modelled as an isotropic material with the above-mentioned stiffness. The results [Figure 5-10] indicate that the predicted response is virtually unchanged with a lower value of modulus of elasticity (E) for the GFRP. The model results for Specimen $C_2$ [Figure 5-10] show slight non-linear behaviour which is a result of several loading steps and non-linearity in the steel.

As illustrated in Figure 5-11, the load-midspan deflection of Specimen $C_4$ is linear up to $\approx 25$ kN, a higher load level compared to Specimen $C_2$. The discrepancy between model and experiment is also less for Specimen $C_4$ (only about 10%). Note that although the
stiffness decreases continually after this point - a feature the model is unable to capture as explained before - there is no sudden shift in the curve (a sign of major cracks) as was seen in Figure 5-10 for Specimen C2. Specimen C4 was fabricated with a radius at the ends of the GFRP section to reduce stress concentrations. During testing, no cracking of the adhesive was observed at these ends, in contrast to Specimen C2. As such, this progressive decrease in stiffness could be attributed to minor local cracks, which were not captured by the naked eye. It could also be due to a non-linear behaviour of the FRP section in flexure which is not being captured by the model. More research is required in this regard. Slip occurred between the web plates and the steel beam at around 40 kN. This resulted in higher decrease in stiffness leading up to failure. The agreement between the model and experiment, for Specimen C4, up this point, is similar to that for Specimen C2 up to the first crack. This is further evidence of the role of premature cracks in the differences between the predicted and experimental behaviour for Specimen C2, as no external cracks in the adhesive were observed for Specimen C4. It is not possible to compare the pre- and post-slip stiffness of the beam. Specimen C4 did not experience any post-slip behaviour.

For Specimen C5 [Figure 5-12], two major cracking events occurred at the levels of loading 20 kN and 30 kN before the sudden failure at about 35 kN. There is slight non-linearity in the load-deflection response due to the progressive crack after the first crack at 20 kN, a feature the model could not duplicate. The discrepancy between model and experiment up to the first crack (20 kN) is ≈18%.
Specimen $C_6$ [Figure 5-13] shows an unusual load-deflection behaviour compared to the other specimens. There was no web plate slip. Moreover, it appears to stiffen at a level of loading equal to 80 kN which could not be captured by the model. This could be attributed to the possible smaller gap for this specimen than the others. The first crack occurred at $\approx 50$ kN. The discrepancy between model and experiment before this point is about 12%.

The first crack in Specimen $C_7$ occurred at 40 kN [Figure 5-14]. The discrepancy between model and experiment before the first crack is about 5%. The specimen witnessed a slight decreasing trend in stiffness after the first crack, followed by a web plate slip at $\approx 70$ kN. The post-slip stiffness is similar to the average pre-slip stiffness.

Specimens $C_6$ and $C_7$ show a hardening behaviour at 5 kN. This could be attributed to the effect of elastomeric pads between loading agent and the spliced beam [Figure 4-9b]. For the purpose of consistency in comparison between stiffness, this initial portion of load-deflection response has been excluded.

A comparison between the results for Specimens $C_2$, $C_5$, $C_6$, and $C_7$ show there is less discrepancy between the predicted and experimentally obtained flexural stiffness as the splice length increases [Figure 5-15]. This could be attributed to fewer premature cracks forming as a result of smaller stress concentrations.

Specimens $C_8$ and $C_9$ were both made with a modified end shape for GFRP section and an enhanced bond surface treatment. The first crack in Specimen $C_8$ occurred at 53 kN followed by web plate slip at 60 kN [Figure 5-16]. The post-slip stiffness was similar to
the average pre-slip stiffness. Neither crack nor slip in web plates was predicted by the model. The discrepancy between model and experiment, before crack, was about 25%. No crack occurred in Specimen C9 until after the web plate slip which occurred at about 60 kN [Figure 5-17]. Post-slip stiffness was higher than pre-slip stiffness which might be attributed to the smaller gap between steel beams. The first crack formed at about 145 kN followed by a continually decreasing stiffness due to progressive crack. The discrepancy between model and experiment, before slip, was similar to Specimen C8 (∼ 25 %). The non-linearity of the predicted load-deflection behaviour is much more pronounced than Specimen C8 due to plastic behaviour of adhesive. This helped in retrieving the same load-deflection response after crack at 145 kN. It predicts a deflection at failure within < 5% of the experimental results.

In general:

- The stiffness predicted by the model is higher than the actual beams by 5% to 25%. This can be attributed to cracking and variability in the epoxy adhesive. This is consistent with experimental observations discussed in Chapter 3 regarding the epoxy adhesive.

- The model is not capable of accurately predicting the load at which slip of the web plate occurs. This would obviously be something that should be addressed in future research if Splice Detail #1 is investigated further.
5.4.3.2 Comparison of Strain Distributions

The predicted strain distribution over the depth of the cross-section at midspan for Specimens C2 and C7 at a level of loading equal to 40 kN is compared with the experimental results in Figure 5-18. Only these two specimens were investigated to save in computational effort. These two specimens were selected since they had the minimum and maximum bond lengths.

The stress distribution is almost linear for Specimen C7 while there is a shear lag effect for Specimen C2. This gives further evidence that specimens with longer splice lengths behave more as a composite section. The results also indicate that the model is capable of predicting strain distribution to an acceptable degree of accuracy (± 25% as per NCHRP 467) for the purposes of a fatigue analysis of modular bridge expansion joints.

5.4.4 Model Verification for Splice Detail #2

5.4.4.1 Load-Deflection Comparison

The predicted results for the load-deflection response of Specimens D1 to D3 are compared to the experimental ones in Figures 5-19 to 5-21.

There is a good agreement between model and experiment for the load-deflection response of Specimen D1 [Figure 5-19] up to ≈ 125 kN, where there is a horizontal shift in the experimental curve. No crack was observed during the experiment at this load level. This could be attributed to the slip in web steel plates, a feature the model is not able to predict. There is a discrepancy between experiment and model (maximum 25% at
around 50 kN) which diminishes as the load is increasing. This could be due to the possible misalignment in the test set-up and the effect of elastomeric pads. The post-slip stiffness is similar to the pre-slip one and almost equal to the stiffness predicted by the model.

The comparison between predicted and experimentally obtained load-deflection response for Specimen $D2$ is illustrated in Figure 5-20. There is a slight horizontal shift in the experimental curve at around 60 kN and 80 kN. The methacrylate-type adhesive was used for this specimen and no crack was observed during the test. As such, these horizontal shifts could be attributed to the slight slips in the web steel plates. The model predicts a load-deflection response almost identical to the experimental results up to $\approx 110$ kN. There is a discrepancy between model and experiment starting from this point up to $\approx 250$ kN. Nonlinearity in the model starts earlier at $\approx 110$ kN whereas the experiment does not show it until $\approx 175$ kN. However, the nonlinearity in the experimental results is greater than the model and they both match each other again at $\approx 250$ kN. The maximum discrepancy in this range is 16%.

Similar trends can be observed for Specimen $D3$ [Figure 5-21]. There is a discrepancy (with a maximum 14%) between model and experiment from 100 kN to 150 kN. The nonlinearity in model starts earlier but at a lower rate. The predicted load-deflection response is almost identical to the experimental results out of this range.

A study on the sensitivity of the results to the midspan gap distance is shown in Figure 5-21. Three different values- namely 1 mm, 3 mm, and 5 mm- for the midspan gap
have been assumed and the predicted load-midspan deflection response for each case has been compared to the experimental results. The results show negligible change with changing gap distance. It only affects the onset of post-gap closure non-linearity. The best match belongs to the case where a 3 mm gap is modelled. This is equal to the average gap measured in the specimens. For the smaller gap, there is a stiffening effect due to the gap closure at lower load levels. This provides an explanation for the behaviour noticed in some of the specimens (e.g. Specimen C6). It is always conservative to ignore the stiffening effect of gap closure.

5.4.5 Stress distribution in adhesive layer

In order to identify the areas prone to cracking in the adhesive, a qualitative comparison between the stress distribution in the adhesive and the crack propagation pattern for the specimens tested is presented in this section. Relatively coarse mesh sizes were used for the purpose of this study. The comparison has been conducted under the same load level.

Stress distribution in the adhesive layer for Specimens C1 and C2 is shown in Figures 5-22 and 5-23 respectively. The half length of the adhesive layer (including midspan gap) is shown. The predicted maximum principal stress at the end corner tips of adhesive is shown. This is the same region first cracks observed. Nevertheless, the results show that the maximum principal stress in the adhesive layer of Specimen C1 is 33% greater than the Specimen C2 for a nominal load. This is contrary to the experimental testing of Specimen C1 which failed at a higher load than Specimen C2. On the other hand, the large stress is distributed over a larger area for Specimen C2. The number of
specimens tested is not statistically significant to definitely state which specimen has more strength. In addition there is a larger scatter for the strength of the epoxy-type adhesive as explained in Chapter 3. Thus, it is not possible to judge the validity of maximum principal stress as a criterion for strength prediction. More research is required.

The stress distribution in the adhesive layer for Specimen $C4$ is shown in Figure 5-24. It can be seen that the stress raiser at the end corners of the FRP section is removed as a result of the radius end shape and the maximum principal stress at that region is about 25% of Specimen $C2$. This explains why no crack was observed in this region in the experiment. The high stress region has moved to midspan and it is possible that the failure was of an intermediate crack nature for Specimen $C4$.

Figure 5-25 illustrates the stress distribution in the adhesive layer for Specimen $C5$. Similar to Specimen $C2$, end corner tips of FRP section are the regions with maximum principal stress, thus prone to cracking. This is consistent with the experimentally observed cracking onset in this region. The maximum principal stress is about 90% that of Specimen $C2$.

The results for Specimen $C6$ and $C7$ are illustrated in Figures 5-26 and 5-27. Again, the maximum principal stress occurs at the end corner tips of the FRP section with a magnitude equal to $\approx 70\%$ and $50\%$ of Specimen $C2$ respectively.

The results for Specimens $C2$, $C5$, $C6$, and $C7$ confirm the experimentally observed crack onset at the end corner tips of the FRP section. Moreover, the predicted strength of the specimens increases as the FRP length increases.
Stress distribution along the adhesive layer for Specimen C8 is compared to the observed crack pattern during the test [Figure 5-28]. The results clearly indicate that cracks form and propagate in the regions with maximum principal stress as predicted by the model. The predicted strength is about 30% of Specimen C2.

The results for Specimen C9 are illustrated in Figure 5-29. Methacrylate-type adhesive is used for this specimen. As such, the von-Mises stress is shown in this figure. There is a singularity area at the gap, so it is not clear whether the maximum stress region has shifted from the end corners to midspan gap or not. The experimental results indicate a crack propagation starting from the end corners. Even if there were local cracks at midspan, it should have occurred at the inner region (near mid longitudinal line) of the adhesive layer as per Figure 5-29. This explains why these cracks were not visible during test. Such cracks, however, did not extend during tests.

The stress distribution within the adhesive layer for Specimen D1 is shown in Figure 5-30. The maximum principal stress is shown as the adhesive used was epoxy. The region with maximum stress (crack-prone region) has shifted to midspan, although no crack was observed experimentally in this region by the naked eye. The maximum stress is along the mid longitudinal axis of the adhesive layer.

The stress distribution in the adhesive layer is similar for Specimens D2 and D3 [Figures 5-31 and 5-32]. The von-Mises stress is shown due to the methacrylate-type adhesive being used. The high stress region is located at midspan, indicating a possible
intermediate crack failure for these specimens. This is in line with what was experimentally observed for Specimen $D3$.

**5.4.6 Strength Prediction**

In the experimental phase almost all specimens failed through adhesive debonding. This failure mode was combined with FRP delamination for Specimens $C8$ and $C9$ and FRP rupture for Specimen $D1$. Specimen $D2$ was the only exception and failed solely through FRP rupture at midspan. The FRP delamination failure mode happens when the FRP resin strength is less than the adhesive strength. This is not possible to be identified by the current method of modelling FRP. Some specimens also experienced web steel plate yielding before failure. In most cases, though, the web plates slipped with little yield, if any.

As such, and to save computational effort, the adhesive layer and FRP plate (or section) were assumed to be the weakest components and the source of failure. The stress level in the adhesive layer was investigated, using the mesh refinement process, to predict the specimen strength as per the method explained in Chapter 3. The maximum principal stress in the FRP was also found and compared to the strength of the FRP material. The lower of the two was taken as the strength of the specimen and compared to the experimental results. This was done only for Specimens $C9$, $D2$, and $D3$ as these had the most promising results. Specimen $D1$ was also investigated to check the adequacy of the proposed method for the specimens made with the epoxy-type adhesive.
It should be realized that the number of experiments done are not statistically significant to give a verdict on the appropriateness of this proposed method. Additional data is required. Nevertheless, it provides a good account on the associated sources of uncertainty and the level of difficulty of this method which will be discussed more in detail later in this chapter.

For Specimens $C9$, $D2$, and $D3$, the maximum von-Mises stress (or alternatively maximum shear strain) in the adhesive is in the midspan near the gap. The same is true for Specimen $D1$ where maximum principal stress is investigated. Since this is a singularity point, stress at a distance 2 mm from the gap has been investigated. This is consistent with the approach adopted in Chapter 3.

The exact value for maximum stress/strain in the adhesive layer is obtained in a mesh refinement process as shown in Tables 5-1 to 5-7 for Specimens $C9$, $D2$, $D3$, and $D1$ respectively. The same convergence criteria as explained in Chapter 3 are used. The maximum stress/strain value is obtained under a nominal applied load equal to 10 kN. This was then compared to the characteristic strengths of the adhesives, as calculated in Chapter 3, to predict the strength of the specimen should the specimen fail in an adhesive debonding failure mode.

The value for maximum principal stress in FRP obtained for Specimens $C9$, $D2$, $D3$, and $D1$ are shown respectively in Tables 5-8 to 5-11. This was later compared to the strength of FRP material being used to predict the strength of the specimen.
The characteristic strain obtained in Chapter 3 for the methacrylate-type adhesive was 0.55 $\varepsilon$. The maximum shear strain in the adhesive layer for Specimens $C9$, $D2$, and $D3$, under a nominal applied load $P=10$ kN, is $4.3 \times 10^{-3} \varepsilon$, $3.3 \times 10^{-3} \varepsilon$, and $6.9 \times 10^{-3} \varepsilon$ respectively. A comparison between the two gives the predicted ultimate strengths for the above-mentioned specimens to be 1279 kN, 1666 kN, and 797 kN respectively. These specimens failed at 180 kN, 258 kN, and 235 (287) kN respectively in practice. A comparison between the model and experiment shows clearly the inappropriateness of maximum shear strain as a means to predict adhesive bond strength.

Next, von-Mises stress was used as the criterion for the characteristic strength of the methacrylate-type adhesive. The characteristic stress obtained in Chapter 3 for the methacrylate-type adhesive was 82 MPa. The maximum principal stress in the adhesive layer Specimens $C9$, $D2$, and $D3$, under a nominal applied load $P=10$ kN, is 3.7 MPa, 2.1 MPa, and 4.3 MPa respectively. A comparison between the two gives the predicted ultimate strengths for the above-mentioned specimens to be 222 kN, 390 kN, and 191 kN respectively. The maximum stress in FRP material for Specimen $D2$, under a nominal applied load $P=10$ kN, is 79 MPa. The strength of Ultra-High Modulus CFRP material used is 1431 MPa. This results in a predicted strength of the specimen of 181 kN. This is less than the predicted strength assuming an adhesive debonding failure mode. As a result, the failure mode for Specimen $D2$ should be a FRP rupture which is in line with the experimental results. The maximum stress in GFRP material for Specimens $C9$ and $D3$ is 7.5 MPa and 14 MPa respectively. The ultimate strength of the GFRP material was 405 MPa based on coupon tests (Chapter 3). This gives the strength of specimens to be
540 kN and 290 kN respectively which are greater than the strengths predicted assuming an adhesive debonding failure mode.

The results are compared to the experiment in Table 5-12. The experimental-to-predicted strength ratio ranges from 0.81 to 1.43. This is a wide range, but should be viewed in light of the statistically small number of experiments and the scatter in the strength of adhesive ($\approx 20\%$). Besides, there is always a reserved strength due to crack propagation. The failure mode is predicted correctly and the crack-prone zones were accurately predicted on a qualitative basis. More research, however, is required to verify the proposed model.

The characteristic stress obtained in Chapter 3 for the epoxy-type adhesive was 77 MPa. The maximum principal stress in the adhesive layer for Specimen $D_1$, under a nominal applied load $P=10$ kN, is 1.6 MPa. A comparison between the two gives the predicted ultimate strengths for the Specimen to be 481 kN should the specimen experience an adhesive debonding failure mode. The maximum principal stress in FRP plate under the nominal applied load 10 kN is 104 MPa. This yields a predicted strength of specimen equal to 138 kN which is about 18% less than the experimental results. Specimen $D_1$ failed at 168 kN in practice. Again, considering the above-mentioned sources of uncertainty, the predicted strength is conservatively acceptable. The actual failure mode was a combination of the predicted one and adhesive debonding.
5.5 Conclusions

A three-dimensional, nonlinear finite element model was developed to study the response of the proposed splice details under static loads. The model was verified against experimental results. The verified model was then used to predict the strength of selected splice details based on the method explained in Chapter 3. The following conclusions could be drawn:

- The response of the spliced details could be predicted accurately by the model on a qualitative basis. The high stress regions prone to failure are adequately identified by model.

- The model could not predict the post-crack, nonlinear behaviour of the spliced beam due to the crack propagation. This is not surprising, though, since the failure criterion for the adhesive is not defined due to lack of the required data.

- The model is not able to predict the web steel plates’ slip. It could be attributed to the incapability of the model to model the crack propagation. This is, however, not critical as the post- and pre- slip load-deflection response of the splice are similar based on the experimental results.

- The model is able to predict the nonlinearity due to the steel beam top flange tips come into contact. It is, however, recommended to ignore this reserved capacity in strength due to the uncertainty of the exact gap between the spliced sections.
The predicted strength of the selected spliced beams, as per the method explained in Chapter 3 was within 70% to 123% of the experimental value. The number of experimental results is not statistically sufficient to give a verdict on the adequacy and accuracy of the proposed method. However, in light of this and also the relatively large scatter for the adhesive strength (Chapter 3), the results are acceptable. The predicted results for 3 out of 4 specimens investigated are conservatively lower than the experimental results.
5.6 REFERENCES

CAN/CSA-S16-01. (2005), Limit States Design of Steel Structures, Canadian Standards Association (CSA), Mississauga, ON, Canada, Reprinted as part of “Handbook of Steel Construction (2007)”, ninth edition, The Emerson Group Ltd., Ontario, Canada


Chapter 5  Behaviour of the proposed splice details under static load- Modelling

Table 5-1- Specimen C9; Maximum shear strain in the adhesive layer

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<th>Step</th>
<th>Mesh size (mm)</th>
<th>Maximum shear strain ( \times 10^3 \varepsilon )</th>
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Table 5-2- Specimen C9; Maximum stress in the adhesive layer

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<th>Maximum von-Mises stress (MPa)</th>
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### Table 5-3: Specimen D2; Maximum shear strain in the adhesive layer

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### Table 5-4: Specimen D2; Maximum stress in the adhesive layer

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Table 5-5 - Specimen D3; Maximum shear strain in the adhesive layer

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Table 5-6 - Specimen D3; Maximum stress in the adhesive layer

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Table 5-7- Specimen D1; Maximum stress in the adhesive layer

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Table 5-8- Specimen C9; Maximum principal stress in FRP

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</tr>
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<td>7.5</td>
</tr>
<tr>
<td>6</td>
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Table 5-9- Specimen *D2*; Maximum principal stress in FRP

<table>
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<td>6</td>
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Table 5-10- Specimen *D3*; Maximum principal stress in FRP

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Table 5-11- Specimen D1; Maximum principal stress in FRP

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Table 5-12- Strength of the selected spliced details; a comparison between model and experiment

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<thead>
<tr>
<th>Specimen</th>
<th>Predicted strength (kN)</th>
<th>Experimental strength (kN)</th>
<th>Difference (%)</th>
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<tr>
<td>C9</td>
<td>222</td>
<td>180.1</td>
<td>+ 23 %</td>
</tr>
<tr>
<td>D2</td>
<td>181</td>
<td>258.2</td>
<td>- 30 %</td>
</tr>
<tr>
<td>D3</td>
<td>191</td>
<td>234.5</td>
<td>- 19 %</td>
</tr>
<tr>
<td>D1</td>
<td>138</td>
<td>168.5</td>
<td>- 18 %</td>
</tr>
</tbody>
</table>
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Figure 5-1 - FE model developed for the control beam with two different mesh types being used.

Figure 5-2 - FE model developed for the Specimen B.
Figure 5-3: Specimen A1; a comparison b/w model and experiment

Figure 5-4: Intact beam; a study on the sensitivity of the model results to the mesh size
Figure 5-5 - Intact beam; a study on the sensitivity of the model results to the mesh type

Figure 5-6 - Specimen B; a comparison between experimental and modelling results
Figure 5-7: Strain distribution along the midspan cross section; a comparison between the experimental and modelling results for Specimen B

Figure 5-8: Specimen B; a study on the sensitivity of the model results to the mesh size
Figure 5-9: Specimen B; a study on the sensitivity of the model results to the adhesive thickness

Figure 5-10: Specimen C2; a comparison between experimental and modelling results
Figure 5-11 - Specimen C4; a comparison between experimental and modelling results

Figure 5-12 - Specimen C5; a comparison between experimental and modelling results
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Figure 5-13 - Specimen C6; a comparison between experimental and modelling results

Figure 5-14 - Specimen C7; a comparison between experimental and modelling results
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Figure 5-15- Discrepancy between model and experiment; a comparison between Specimens C2, C5, C6, and C7

Figure 5-16- Specimen C8; a comparison between experimental and modelling results
Figure 5-17: Specimen C9; a comparison between experimental and modelling results

Figure 5-18: Stress distribution along midspan cross section; a comparison between the experimental and modelling results (P=40 kN)
Figure 5-19: Specimen D1; a comparison between experimental and modelling results

Figure 5-20: Specimen D2; a comparison between experimental and modelling results
Figure 5-21 - Specimen D3; a comparison between experimental and modelling results

Figure 5-22 - Specimen C1; stress distribution in adhesive layer
Figure 5-23- Specimen C2; stress distribution in adhesive layer

Figure 5-24- Specimen C4; stress distribution in adhesive layer
Figure 5-26 - Specimen C6; stress distribution in adhesive layer
Figure 5-27- Specimen C7; stress distribution in adhesive layer

Figure 5-28- Specimen C8; stress distribution in adhesive layer
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Figure 5-29- Specimen C9; stress distribution in adhesive layer

Figure 5-30- Specimen D1; stress distribution in adhesive layer
Figure 5-31- Specimen $D_2$; stress distribution in adhesive layer

Figure 5-32- Specimen $D_3$; stress distribution in adhesive layer
CHAPTER 6

FATIGUE TESTING OF SPLICE DETAIL #2

6.1 INTRODUCTION

The most important feature of any proposed splice detail for a modular bridge expansion joint centre-beam is its resistance against fatigue. The results in Chapter 4 showed that the Splice Detail #2 with CFRP and the methacrylate-type adhesive not only had the best ultimate strength, but also showed linear-elastic behaviour up to 75% of its ultimate strength. Several cycles of loading-unloading in the range 20 to 80 kN showed no significant loss of stiffness [Figures 6-1 and 6-2]. No cracks at the end of these cycles were observed. However, due to a limited supply of CFRP, Splice Detail #2 with GFRP and the methacrylate-type adhesive was chosen for the fatigue. This splice detail showed the second best behaviour in terms of strength (Chapter 4). It showed linear-elastic behaviour up to 55% of its ultimate strength. Several cycles of loading/unloading in the range 20 to 90 kN did not show any trace of cracking or significant loss of stiffness [Figures 6-3 and 6-4].

In this chapter, the design of fatigue test set-up is presented. Then, the fatigue testing of the Splice Detail #2 with GFRP and the methacrylate-type adhesive is described and the experimental results obtained from fatigue tests are discussed.

The results will be compared, next, to that of the preliminary fatigue life assessment conducted using the verified finite element model developed in Chapter 5.
6.2 Design of Fatigue Test Set-up

A special fatigue test set-up was designed for the purposes of this study. The conceptual design is shown in Figure 6-5. The set-up was designed to be installed in a typical MTS testing machine. This allowed the fatigue tests to be conducted with control over applied load and stroke. The set-up consisted of two main hollow steel structural (HSS) segments, each gripped by the MTS jaws (shown as upper and bottom green parts in Figure 6-5b) through welded T-sections. Supports and loading elements are HSS sections bolted to the main segments. The designed fatigue test set-up is able to accommodate the various spans typical of modular bridge expansion joint centre-beams (between 0.8 and 1 m). The distance between the applied loads can also be varied. Slotted holes are provided in the main segments for this purpose. The set-up is also designed to accommodate the simultaneous application of vertical and horizontal loads, typical of modular bridge expansion joints. This is accommodated by rotating the centre-beam along its longitudinal axis to any desired angle, as shown in Figures 6-6 and 6-7. The detailed drawings of all the components of the fatigue test set-up are presented in Appendix I.

The modular bridge expansion joint centre-beam is tested as a simply supported single-span beam despite being a continuous beam in practice. This was mainly for the purpose of simplicity. The loading requirements for a single span beam to satisfy fatigue limit states were discussed in Chapter 4. The assumption in this approach is that the results from single span tests can be extrapolated to predict the behaviour of continuous beams.
6.2.1 Design

The fatigue test set-up was designed as explained in detail in Appendix J.

The following assumptions were made:

- Two cases of the simultaneous application of a horizontal force equal to 25% and 50% of the applied vertical load were considered. These cases were simulated by tilting the specimen to the angles $\theta$ equal to 14° and 26.6° respectively as shown in the drawings (Appendix I). The latter was used to calculate the maximum load applied.

- The maximum fatigue load range is 56 kN as per CHBDC 2006 (Chapter 4). To ensure that the produced tensile stresses never pass zero, a minimum applied load of 4 kN was considered. This complies with the provisions provided in NCHRP Report 402. Thus the maximum applied load in a fatigue test is 60 kN.

- An additional safety factor equal to 3 was taken, unless otherwise stated.

The design load was, thus, calculated to be 200 kN as follows [Figure 6-7]:

\[ V = 60 \times 3 = 180 \text{ kN} \quad (6 - 1) \]

\[ H = 50\% \times V = 90 \text{ kN} \quad (6 - 2) \]

\[ R = \sqrt{V^2 + H^2} \approx 200 \text{ kN} \quad (6 - 3) \]

The maximum principal tensile stress in the components were found using finite element analysis and compared to fatigue thresholds specified for different AASHTO categories.
[equivalent to CAN/CSA-S16-01]. Finite element analysis was performed in a commercial package, namely ABAQUS. Steel was defined as a simple bilinear elasto-plastic material with yield strength and modulus of elasticity equal to 350 MPa and 200 GPa respectively. Tetrahedron (C3D10M) elements were used as explained in Chapter 3. The results from the finite element analysis were further checked using simple approximate hand calculations. Table 6-1 provides a comparison between the results obtained from the two methods of analysis used and the fatigue threshold for each component. The components of the set-up are labelled in Figure 6-5.

### 6.3 Experimental Program

#### 6.3.1 Introduction

Fatigue tests (Specimens E1 and E2) were conducted only for Splice Detail #2 made with GFRP plates and the methacrylate-type adhesive. These specimens were replicates of Specimen C3 (Chapter 4). Full discussion on the fabrication process and the material used is presented in Chapter 4. Splice Detail # 2 was chosen due to its superior response to the static loads. GFRP plates were used due to lack of access to Ultra-High Modulus CFRP plates.

The loads were applied vertically over two rectangular areas (each 0.2 × 0.103 m) spaced 0.4 m centre-to centre apart. This area was the contact area between the centre-beam (W 100 × 19) and the fatigue resistant elastomeric pads used between the specimen and
the HSS sections responsible to apply loads (HSS 152 ×13). It is noteworthy to mention that the wheel loads are applied as rectangular patches in practice. No horizontal loads were taken into consideration.

The supports were spaced 1 m centre-to-centre. HSS 152 × 13 sections were used as supports. This is similar to the support beams used in modular bridge expansion joints. Fatigue-resistant elastomeric pads were also placed between the specimen and the supports.

The specimen was placed between the HSS sections acting as supports and loading agents so that it was symmetrical, in both front and side directions, with respect to the axial axis of the MTS machine. The elastomeric pads were then placed between the HSS sections and specimen and secured using C-clamps as illustrated in Figure 6-8. A minimum of 4 kN load was then applied as the lower bound of the applied fatigue load.

The equivalent fatigue loading requirement for a single span beam, as discussed in Chapter 4, is 56 kN as per the Canadian Highway and Bridge Design Code (CHBDC 2006). The load should not pass zero to produce the maximum stress in the components (NCHRP Report 402). A minimum load of 4 kN was thus used. The loading cycle was therefore 4 kN to 60 kN.

The specimens $E1$ and $E2$ were tested in a 1000 kN MTS testing machine [Figure 6-8] under a sinusoidal load cycle with a frequency equal to 0.6 Hz. This was the maximum frequency the whole system could achieve without excessive shattering of the pipes and connections.
“The emphasis in fatigue testing of (Modular Bridge Expansion Joint) details”, NCHRP Report 402 states, “should be on defining the fatigue threshold”. Modular Bridge Expansion joints are expected to experience more than 10 million cycles over the expected life of the deck [NCHRP Report 402]. Thus, the ideal is to develop a splice detail with a characteristic S-N curve having a Constant Amplitude Fatigue Limit (CAFL) starting at maximum 10 million cycles of loading. The fatigue limit should also be greater than the required stress range as per CHBDC. The S-N curve for the proposed splice detail is unknown. It is preferred to comply at least with AASHTO Category C [MTO correspondence].

The critical component the maximum stress should be measured at in the splice detail is not clear. The scatter in the data from actual fatigue tests is typically so high that using a verified analysis model (with the results within ± 25% of the actual measurements) in fatigue life appraisal is preferred [NCHRP Report 402]. As such, it was decided to run two fatigue tests to 1,000,000 cycles and compare the results with the preliminary fatigue assessments performed using the verified finite element model introduced in Chapter 4. Further tests, at least 10 in total as per NCHRP Report 402, are required to establish the characteristic S-N curve of the proposed splice detail. However, the model could be used to modify the proposed detail so that there is an infinite life for at least 10 million cycles of loading. This will be discussed in detail later.
6.3.2 Experimental Results and Discussion

Specimen E1 failed at 719,347 cycles of loading. The failure was a crack in the web splice plates at midspan (both sides) [Figure 6-9] plus an intermediate crack delamination [Figure 6-10]. It is not, however, known which one happened first. Initial cracks formed in the adhesive layer at about 50,000 cycles. The cracks started at midspan (in the form of an intermediate crack) and propagated towards both ends in a Sliding Mode (or Fracture Mode II; Bannantine et al. 1990). These cracks formed in the adhesive layer corresponding to both upper and bottom FRP plates [Figure 6-10]. The crack propagation rate was not recorded precisely during the test. However, on a qualitative basis, the crack propagation rate was decreasing. The successive crack length increase at 50,000, 100,000, and 200,000 were about 35, 20, and 10 mm respectively. The crack length did not increase significantly after that. On the other hand, the cracked surface of web steel plates, illustrated in Figure 6-11, consists of a series of zigzag, rough surfaces. This implies fatigue to be the cause of this crack. As a result, it is believed that the web steel plates were cracked as a result of fatigue and failed first. This resulted in an excessive midspan deflection. The available intermediate crack was consequently forced to propagate towards one end which caused system failure.

Specimen E2 survived one-million cycles of loading. Cracks occurred in the adhesive layer at midspan, similar to the case of Specimen E1. Crack propagation was in the same mode, i.e. sliding, at a qualitatively decreasing rate as observed for Specimen E1. Specimen E2 was subsequently tested under static loads to failure (Specimen D4) as discussed in Chapter 4. The loss in strength or stiffness, as a result of being exposed to
fatigue loading, was negligible. No adverse effects on the static behaviour, as a result of the cracks, were observed.

6.4 Preliminary Assessment

The verified model for Specimen $D3$ (or its replicate Specimen $D4$) was used to conduct a preliminary assessment of the fatigue life. The method used was based on finding the maximum principal stress range in all the components, under the required fatigue loading, and comparing that to the stress-life (S-N) characteristic curve for each material.

No information was found in the literature for the fatigue properties of the methacrylate-type adhesive. Neither was anything found for the epoxy-type adhesive. Methacrylate adhesive has been recently used successfully in the applications where excellent fatigue life is required. This includes, but is not limited to boats, wind turbine blades and truck bed structures [Daggett 2004]. This adhesive has also proved to be extremely useful in applications where very short fixture times and strong impact resistance are required [Dunn 2004]. Due to lack of additional data, and until more research is conducted, it was assumed that the methacrylate-type adhesive would not be the critical component in fatigue.

The constant amplitude stress-life curve for GFRP is linear with a slope of 10% when plotted on linear-log axes and it is reported to not have a fatigue limit [ACI 440.2R-08].
Assuming 406 MPa for the tensile strength of GFRP sections, the GFRP will have a fatigue strength of 162 MPa at a fatigue life of one-million cycles.

Steel theoretically has an infinite fatigue life at about 50% of its ultimate strength and lower (Bannantine et al. 1990). The onset of this corresponds to a fatigue life of one-million cycles. Before this, amplitude stress-life curve for steel is linear with a slope of 8.5% when plotted on log-log axes. Assuming 450 MPa for the tensile strength of steel section, it has a fatigue strength of 225 MPa for a fatigue life of one-million cycles and more. However, this is true only for well-polished steel with no defects (residual stresses etc.). For structural steel, it is more likely to have a basic fatigue limit consistent with AASHTO Category A. Based on this category, plain steel structural elements have a fatigue strength of 165 MPa for a fatigue life of 1.82 million cycles and more [CAN/CSA S16-01].

The maximum principal stress range, under the applied load, is predicted to be 211 and 80 MPa for steel and GFRP respectively. The maximum stress range in GFRP plate is well below the fatigue strength of 162 MPa at fatigue life of one-million cycles. The maximum stress range in steel, on the other hand, is greater than the theoretical fatigue threshold (165 MPa). For the applied stress range $F_{sr} = 211$ MPa, and for AASHTO Category A, the predicted fatigue life is:

$$ N = \frac{\gamma}{(F_{sr})^3} = \frac{8190 \times 10^9}{(200)^3} = 871840 \text{ (Cycles)} \quad (6-4) $$
The maximum stress in steel occurs at the lower side of steel plates about 0.04 m from midspan as shown in Figure 6-12. As such, the possible failure mode for the spliced beam would be predicted as a crack in the steel plates in the place of maximum stress, i.e. at the lower side of steel plates about 0.04 m from midspan. This would cause excessive deflection at midspan which might cause either delamination, debonding, or rupture of FRP plates.

6.5 DISCUSSION

Specimen E2 survived one-million cycles. Specimen E1, on the other hand, failed at 719,347 cycles. The predicted fatigue life was 871,840 cycles. This discrepancy could be attributed to the typical scatter in results for fatigue life of steel. Cracks initiated in the steel web plates, at the same region as predicted by model. This was followed by sudden intermediate crack (IC) delamination/debonding.

It should be noted that large scatter is typically observed for fatigue test data. More experimental results are required to predict the fatigue behaviour of a splice detail. NCHRP Report 402 requires at least 10 full size specimens tested at various stress ranges to develop a reliable fatigue life curve for that specimen. Unfortunately, it was not possible to fulfill a complete study program on the fatigue resistance of the proposed splice details mainly due to time limits. Although more experimental work is required to obtain a sound knowledge of the behaviour of the proposed Splice Detail # 2 under fatigue, the limited results obtained for one of the proposed details seem to be promising.
The results are consistent with the developed verified model. This model was further used to investigate a modified configuration that would reduce the stress in the steel below fatigue limit. Steel web plates thickness was increased from 6 mm to 10 mm. This 67% increase in thickness resulted in a 13% reduction in maximum stress in steel plates. The maximum stress in steel plates, as predicted by model, is 183 MPa. The fatigue life equivalent to this stress range is 1,336,382 cycles which is equivalent to a 53% increase in fatigue life. Increasing steel web plate is an option. However, there is a limit for it due to the limited workspace between adjacent centre-beams in modular bridge expansion joint. More research is required to be done in this regard.

Using Ultra-High Modulus CFRP plates, instead of GFRP plates, in Splice Detail #2 increased both stiffness and ultimate strength of the splice detail as discussed in Chapter 4. Such a splice detail also demonstrated linear-elastic load-deflection behaviour up to a higher load level (Chapter 4). Thus, Splice Detail #2 with CFRP plates is expected to demonstrate an improved fatigue performance compared to the splice with GFRP tested in the current chapter. However, the limited ductility and the associated failure mode (FRP rupture) of Splice Detail #2 with Ultra-High Modulus CFRP plates is a concern. Using CFRP plates with a lower modulus of elasticity is proposed as an alternative. Such a CFRP material has a higher ultimate strain which results in a potential change in failure mode, from FRP rupture to adhesive debonding, and, as a consequence, higher ductility. Further research is recommended to investigate the fatigue performance of Splice Detail #2 with CFRP plates.
6.6 CONCLUSIONS

Two fatigue tests at 1,000,000 cycles have been performed on Specimen D3. A preliminary fatigue life assessment was performed using the developed finite element model in Chapter 5 and the fatigue performance of the materials used in the constituent components of the splice detail. The following conclusions could be drawn:

- The overall fatigue behaviour of the proposed Splice Detail # 2, in the case a methacrylate-type adhesive and GFRP material are used, seems promising. It had a fatigue life between 719,347 and 1,000,000 when subjected to 56 kN, which is the CHBDC fatigue loading.

- The 3-dimentional finite element model developed in Chapter 5, used successfully in predicting the fatigue life of the proposed splice detail. This model could be used to investigate the required modifications in the geometry and material properties in order to increase the fatigue behaviour of the proposed detail at a lower cost and time.

- The proposed method of using finite element model in predicting the fatigue life behaviour of the proposed splice detail should be further verified by complementary fatigue tests. Such fatigue tests are required, as per NCHRP 402, to provide a characteristic S-N curve for the best promising detail.

- Research is required to investigate the fatigue behaviour of the materials involved particularly the adhesives being used.
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- The enhanced method of the bond surface treatment was used in the specimens tested based on the results obtained in Chapters 3 and 4. The notches introduced to the steel surface in this method, however, may reduce the fatigue life of steel component. Further research is required to investigate this.
6.7 References

ACI 440.2R-08 (2008). “Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures,” American Concrete Institute, 38800 Country Club Drive, Farmington Hills, MI, 48331, USA


CHBDC. (2006). *CAN/CSA-S6-06, Canadian Highway Bridge Design Code*, Canadian Standards Association (CSA), Mississauga, ON, Canada


MTO correspondence (2008-2009). Private correspondence between Ministry of Transportation of Ontario and Queen’s researchers regarding the project.

Table 6-1 - Fatigue test set-up design; a comparison between the results from two analysis methods used

<table>
<thead>
<tr>
<th>Element</th>
<th>Maximum principal stress (MPa)</th>
<th>Limit (MPa) (Category A)</th>
</tr>
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<td>FEA</td>
<td>Approximate hand analysis</td>
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<tr>
<td>A</td>
<td>120</td>
<td>134</td>
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<tr>
<td>B</td>
<td>152</td>
<td>54</td>
</tr>
<tr>
<td>C</td>
<td>117</td>
<td>117</td>
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</tbody>
</table>

*Elements are labelled in Figure 6-5
Figure 6-1- Specimen D2; Load-midspan deflection curve

Figure 6-2- Specimen D2; Load-midspan deflection response for a series of cyclic loads applied between 20 to 80 kN.
Figure 6-3- Specimen D3; Load-midspan deflection curve.

Figure 6-4- Specimen D3; Load-midspan deflection response for a series of cyclic loads applied between 20 to 90 kN.
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Figure 6-5- Fatigue test set-up; a) side view; b) front view

Figure 6-6- simultaneous application of vertical and horizontal loads by rotating the specimen
Figure 6-7- Vertical and horizontal components of the applied load on a rotated specimen the specimen

Figure 6-8- Fatigue test set-up
Figure 6-9- Specimen $E1$; failure under fatigue

Figure 6-10- Intermediate cracks propagated into adhesive
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Figure 6-11- Web steel plate; crack surface

Figure 6-12- Maximum principal stress in the web steel plates under fatigue loads
CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 Summary

The main objective of this research was to explore new fatigue-resistant field splice details for modular bridge expansion joints. Two innovative, hybrid steel/FRP details were proposed. No previous studies were found in the literature on the potential use of FRP material as a means to splice steel beams. As such, the proposed details were examined thoroughly under vertical static loads to study their behaviour and investigate their compliance with the requirements for modular bridge expansion joints. The effect of several parameters was studied. A three-dimensional, non-linear finite element model was developed and verified against the experimental results to study the stress distribution within each component of the splice details. A method was also proposed to predict the strength of the splice details using the developed model. The proposed model could be used as a means to conduct further parametric studies.

The above-mentioned method is based on the ‘characteristic strength’, as defined in Chapter 3, of the adhesives being used. The effect of two different adhesives was studied using double shear lap splice tests. Several parameters of the adhesive bond were studied. The experimental results were then incorporated into a nonlinear finite element model to estimate the characteristic strength of each adhesive.
Chapter 7

Summary and Conclusions

The fatigue resistance of the proposed details, despite being the most important feature, was only studied to a limited extent and just for one of the most promising details. This was mainly due to time limits. A special fatigue test set-up was designed and two experimental fatigue tests, at the required load range, were performed. As explained in Chapter 4, the required equivalent fatigue load range is 56 kN as per CHBDC 2006. The results were then compared to a preliminary fatigue life assessment of the detail using the developed finite element model. More studies, however, are required to obtain a sound knowledge of the fatigue behaviour of the splice detail. The results could also be used to verify the adequacy of the proposed method of using the validated model in fatigue life appraisal.

7.2 Conclusions

From the proposed splice details, Splice Detail #2 with methacrylate adhesive yielded the most promising results in the static phase. The specimens spliced using this detail have 87% to 107% of the intact beam strength and 67% to 102% of its stiffness. Using CFRP material in this splice detail resulted in higher strength and stiffness with a greater elastic load range, whereas the detail with GFRP plates had superior ductility.

The adhesive bonds made using the methacrylate-type adhesive showed superior strength and ductility compared to the epoxy-type adhesive in both splice details. The results, backed up by independent shear lap tests, showed clearly the inadequacy of relying on the reported nominal properties for adhesive by the manufacturers. The bond strength of
any adhesive should be independently investigated using shear lap splice tests under similar conditions in practice.

The enhanced method proposed for bond surface preparation (Chapter 3) resulted in 15% to 43% higher bond strength. The results thereof were also more consistent. The enhanced method of bond surface treatment is therefore recommended for all such applications.

A new method is proposed to predict the strength of the adhesively bonded systems. The previous methods proposed by Cadei et al. (CIRIA C595, 2004) and Hart-Smith 1973 were shown to be inadequate for the current complicated system of the splice detail (Chapter 3). The current proposed method involves developing a three-dimensional, non-linear finite element model and conducting shear lap splice details as described in Chapters 3 and 5. The predicted strengths range from 70% to 123% of the experimental results. In three out of four examined cases, the results were conservative. It should be noted that the number of the current experimental results is not statistically sufficient to validate the proposed method. There are also some limits to its applicability as discussed in Chapter 5; the model is not able to predict the slip between web steel plates and steel beam, neither it can predict the post-crack behaviour of adhesively bonded system due to lack of post-failure properties of the adhesive. Nevertheless, the method is promising. More research is required in this regard.

The developed finite element model, however, was proved to be very useful and informative, on a qualitative basis, in the study of the behaviour of the proposed splice
details. It could be used, therefore, reliably to conduct parametric studies at a considerably lower price and higher speed.

The fatigue behaviour of Splice Detail #2, made with GFRP plates and the methacrylate-type adhesive, was investigated to a limited extent and seems promising. It had a fatigue life of 720,000 to 1,000,000 cycles under the required load range, namely 56 kN. The proposed finite element model was used to assess the fatigue life of the detail. The result (870,000) was in agreement with the experimental ones within the scatter typical of fatigue test results. The experimental results, however, were not statistically sufficient to validate this method. Neither were they enough to provide a reliable picture of the fatigue behaviour of the splice detail under different conditions.

Conclusions are discussed in more detail at the end of each chapter.

7.3 Recommendations for Future Work

The research carried on under the current study was the first step in investigating the potential use of FRP material as a means to splice steel beams. Different details were tested and the effect of several parameters was examined. The main focus was its application for modular bridge expansion joints. The preliminary results are promising.

The following are recommendations for future research:

- To validate the proposed method of predicting the splice strength using a statistically sufficient number of experimental tests.
• To obtain the constitutive models for adhesives. The constitutive model for the adhesive should be incorporated into the proposed model to enable it to predict the crack propagation and post-crack behaviour of the splice system.

• To obtain the Wöhler (S-N) curve for fatigue behaviour of the proposed splice detail as per NCHRP Report 402 requirements (Chapter 6).

• To study the behaviour of the splice detail under combined vertical and horizontal loading as per NCHRP Report 402 (Chapter 6).

• To study the behaviour of the splice detail under negative bending.

• To investigate the negative effects of the enhanced bond surface preparation method (notches on the steel surface) on the fatigue performance of splice details.

• To investigate the fatigue properties of the adhesives and FRP material used for structural purposes. This is required to validate the proposed numerical fatigue appraisal method as explained in Chapter 6.

• To conduct a parametric study, using the validated finite element model, to optimize the splice detail to best meet the requirements for modular bridge expansion joints (and in general for each specific application).

• To conduct a full scale fatigue testing, using modular bridge expansion joint prototypes, to study the effect of continuity and complexity of the system on the splice behaviour.
• To conduct a comprehensive field experimental program to investigate the behaviour of the proposed splice detail in practice.

• To explore potential alternative applications for such hybrid splice details such as railroads, etc.

• To conduct a comprehensive study on the adhesive selection for such purposes. It is proposed to conduct an exhaustive research to study the role of different adhesive parameters such as adhesive type, tensile strength, shear strength, etc. on the bond strength and quality between FRP and steel.

• To investigate the durability issues for such proposed splice details in field.
Appendix A

Material specifications for GFRP pultruded sections
Below are test results for typical coupon properties of Bedford Reinforced Plastics’ structural fiberglass profiles (Standard, Fire Retardant, & Vinylester shapes). Properties are derived per the ASTM test method shown. Synthetic surfacing veil and ultraviolet inhibitors are standard.

### TYPICAL COUPON PROPERTIES

<table>
<thead>
<tr>
<th>MECHANICAL PROPERTIES</th>
<th>ASTM</th>
<th>Units</th>
<th>Value</th>
<th>ENGLISH</th>
<th>Metric</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Stress, LW</td>
<td>D-638</td>
<td>psi</td>
<td>30,000</td>
<td>MPA</td>
<td>206.8</td>
<td></td>
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<tr>
<td>Tensile Stress, LW</td>
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<td>psi</td>
<td>7,000</td>
<td>MPA</td>
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<td>GPA</td>
<td>17.2</td>
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<tr>
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<td>10^6 psi</td>
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<td>GPA</td>
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<td>Compressive Stress, LW</td>
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<td>MPA</td>
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<td></td>
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<tr>
<td>Compressive Stress, CW</td>
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<td>MPA</td>
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<td>Flexural Stress, CW</td>
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<td>MPA</td>
<td>68.9</td>
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<tr>
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<td>Flexural Modulus, CW</td>
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<tr>
<td>Modulus of Elasticity, E</td>
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<tr>
<td>Full Section</td>
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<tr>
<td>Shear Modulus</td>
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<td></td>
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<tr>
<td>--</td>
<td></td>
<td>10^6 psi</td>
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<td>GPA</td>
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<td>Short Beam Shear</td>
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<tr>
<td>Punch Shear</td>
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<td>Notched Izod Impact, LW</td>
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<td>J/mm</td>
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<tr>
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<td>J/mm</td>
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<tr>
<td>Barcol Hardness</td>
<td>D-2583</td>
<td>----</td>
<td>45</td>
<td></td>
<td>---</td>
<td>45</td>
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<tr>
<td>24 Hour Water Absortion</td>
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<td>% max.</td>
<td>.045</td>
<td></td>
<td>% max.</td>
<td>.45</td>
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<tr>
<td>Density</td>
<td>D-792</td>
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<td>g/cc</td>
<td>1.72-1.94</td>
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<tr>
<td>Coefficient of Thermal Expansion, LW</td>
<td>D-696</td>
<td>10^6 in./°F</td>
<td>7</td>
<td></td>
<td>10^6 cu./cm./°C</td>
<td>12</td>
</tr>
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<table>
<thead>
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<th>ELECTRICAL PROPERTIES</th>
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<th>Value</th>
<th>ENGLISH</th>
<th>Metric</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Arc Resistance, LW</td>
<td>D-495</td>
<td>seconds</td>
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<td>seconds</td>
<td>120</td>
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<tr>
<td>Dielectric Strength, LW</td>
<td>D-149</td>
<td>kv/in.</td>
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<td></td>
<td>kv/mm</td>
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<tr>
<td>Dielectric Strength, PF</td>
<td>D-149</td>
<td>volts/mil.</td>
<td>200</td>
<td></td>
<td>volts/mil.</td>
<td>200</td>
</tr>
<tr>
<td>Dielectric Constant, PF</td>
<td>D-150</td>
<td>@60hz</td>
<td>5</td>
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<td>5</td>
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</table>

Fire Retardant Polyester and Fire Retardant Vinylester Structural Profiles:

### FLAMMABILITY PROPERTIES

<table>
<thead>
<tr>
<th>FLAMMABILITY PROPERTIES</th>
<th>ASTM</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel Test</td>
<td>E-84</td>
<td>Flame Spread</td>
<td>25 max.</td>
</tr>
<tr>
<td>Flammability</td>
<td>D-635</td>
<td>— —</td>
<td>Nonburning</td>
</tr>
<tr>
<td>UL</td>
<td>94</td>
<td>VO</td>
<td></td>
</tr>
<tr>
<td>NBS Smoke Chamber</td>
<td>E-662</td>
<td>Smoke Density</td>
<td>600-700</td>
</tr>
</tbody>
</table>

**LW** = Lengthwise  **CW** = Crosswise  **PF** = Perpendicular to Laminate Face
Appendix B

Material specifications for
SP systems Spabond 345
Spabond 345
Epoxy Adhesive System

- High strength and toughness
- Excellent gap filling properties
- Designed for cartridge and mixing machine dispense
- Three hardener speeds give a range of working times / clamp times
- Low exotherm and shrinkage
- Temperature performance up to 84°C

Introduction

Spabond 345 is a toughened, high performance adhesive system ideal for bonding large structures where substrate surfaces have uneven geometry. The product has a thick, paste-like consistency, and can be applied without sag in thicknesses of over 30mm at 15°C, making it ideal where large, uneven vertical gluelines are required.

The product has a 2:1 mix ratio by volume. To aid mixing, the components are pigmented to give visual indication of mix quantity. The Fast hardener is coloured purple, but there is also a black version. This is useful for improving the cosmetic appearance of bondlines involving exposed carbon composites.

Spabond 345 is available in 400ml cartridges, pails and drums.
Instructions for Use

The product is optimised for use at 15 - 25°C. At lower temperatures the components thicken and may eventually become unworkable. To ensure accurate mixing and good workability pre-warm the resin & hardener as well as the surfaces to be bonded before use.

Surface Preparation

Before using the product ensure that surfaces to be bonded are clean, dry and dust-free. Prepare all surfaces by abrading with medium grit paper or other suitable abrasive, remove dust then wipe with acetone or SP Fast Epoxy Solvent (Solvent A).

Metals usually require a chemical pre-treatment to create the best bond. Please contact sp for a Guide to Surface Preparation and Pre-treatments.

Ensure that polyester or vinylester laminates are fully cured before bonding, then prepare as above.

When bonding epoxy laminates, the use of a suitable Peel Ply as the last stage in their manufacture is recommended, otherwise prepare as above. Trials may be required to test Peel Ply suitability.

For ferrocement, etch with 5% solution of hydrochloric acid, wash with fresh water, then dry.

Mixing & Handling

Spabond 345 resin should be combined with Spabond 345 fast (purple or black), Spabond 345 slow (red) or extra slow (blue) hardener in the following mix ratio:

<table>
<thead>
<tr>
<th>Spabond 345 resin</th>
<th>Spabond 345 hardener</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 : 48 (by weight)</td>
<td></td>
</tr>
<tr>
<td>100 : 50 (by volume)</td>
<td></td>
</tr>
</tbody>
</table>

Mix thoroughly for at least one minute, paying particular attention to the sides and bottom of the mixing vessel, to ensure no streaks remain. Once fully mixed the adhesive should have a uniform brown, black, orange or pale green colour, depending on the hardener used. Use from pot quickly to maximise resin working life.

Cartridge Use

If dispensing product from twin cartridges with a mixing/dispensing head, please discard the first mix head length of resin and hardener components, prior to applying adhesive to the job, in order to ensure thorough mixing of the system. We recommend the use of a new mix head for each application, particularly where the time between each application approaches the pot life.

Properties

<table>
<thead>
<tr>
<th>Component Properties</th>
<th>Resin</th>
<th>Hardener</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Fast</td>
</tr>
<tr>
<td>Mix Ratio (by weight)</td>
<td>100</td>
<td>48</td>
</tr>
<tr>
<td>Mix Ratio (by volume)</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>Viscosity @ 15°C (cP)</td>
<td>125,000</td>
<td>45,000</td>
</tr>
<tr>
<td>Viscosity @ 20°C (cP)</td>
<td>105,000</td>
<td>30,000</td>
</tr>
<tr>
<td>Viscosity @ 25°C (cP)</td>
<td>95,000</td>
<td>20,000</td>
</tr>
<tr>
<td>Viscosity @ 30°C (cP)</td>
<td>70,000</td>
<td>15,000</td>
</tr>
<tr>
<td>Shelf Life (months)</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Colour</td>
<td>yellow</td>
<td>purple</td>
</tr>
<tr>
<td>Mixed Colour</td>
<td>brown</td>
<td>pink</td>
</tr>
<tr>
<td>Component Dens. (g/cm³)</td>
<td>1.17</td>
<td>1.08</td>
</tr>
<tr>
<td>Mixed Density (g/cm³)</td>
<td></td>
<td>1.14</td>
</tr>
<tr>
<td>Hazard Definition</td>
<td>Xi, N</td>
<td>C, N</td>
</tr>
</tbody>
</table>

Notes:
1. Due to the thixotropic and filled nature of this system, these values are only indicative.
2. For an explanation of test methods used see ‘Formulated Products Technical Characteristics’.
3. All figures quoted are indicative of the properties of the product concerned. Some batch to batch variation may occur.
4. † All times are measured from when resin and hardener are first mixed together.
Properties (Cont’d)

Cured System Properties

<table>
<thead>
<tr>
<th>Room Temp. Cure (28 days @ 21°C)</th>
<th>Cured 24 hours @ 21°C+16 hours @ 50°C</th>
<th>Cured 5 hrs @ 70°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast</td>
<td>Slow</td>
<td>Extra Slow</td>
</tr>
<tr>
<td>Tg DMTA (Peak Tan δ)(°C)</td>
<td>66.8</td>
<td>70.0</td>
</tr>
<tr>
<td>Tg Ult - DMTA (°C)</td>
<td>91.7</td>
<td>106.5</td>
</tr>
<tr>
<td>Tg2 - DSC (°C)</td>
<td>54.6</td>
<td>58.9</td>
</tr>
<tr>
<td>Tg1 - DMTA (°C)</td>
<td>57.1</td>
<td>55.5</td>
</tr>
<tr>
<td>Cured Density (g/cm³)</td>
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<td>-</td>
</tr>
<tr>
<td>Sag Resistance (mm)</td>
<td>17</td>
<td>16</td>
</tr>
<tr>
<td>Cured Density (g/cm³)</td>
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<td>-</td>
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<tr>
<td>Linear Shrinkage (%)</td>
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<td>0</td>
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<tr>
<td>Cleavage Strength (kN)</td>
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<td>12.30</td>
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<tr>
<td>Shear Strength on Steel (MPa)</td>
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<tr>
<td>Shear Strength Wet Retention (%)</td>
<td>95.4</td>
<td>92.9</td>
</tr>
</tbody>
</table>

Notes:
*Due to the thixotropic and filled nature of this system, these values are only indicative.

For an explanation of test methods used see ‘Formulated Products Technical Characteristics’.

All figures quoted are indicative of the properties of the product concerned. Some batch to batch variation may occur.

† All times are measured from when resin and hardener are first mixed together.

Working Properties vs. Temperature

<table>
<thead>
<tr>
<th>Initial Mixed Viscosity (cP)</th>
<th>15°C</th>
<th>20°C</th>
<th>25°C</th>
<th>30°C</th>
<th>15°C</th>
<th>20°C</th>
<th>25°C</th>
<th>30°C</th>
<th>15°C</th>
<th>20°C</th>
<th>25°C</th>
<th>30°C</th>
</tr>
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<tbody>
<tr>
<td>Fast</td>
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<td>42000</td>
<td>34000</td>
<td>27000</td>
<td>106000</td>
<td>87000</td>
<td>75000</td>
<td>64000</td>
<td>74000</td>
<td>44000</td>
<td>36000</td>
<td>24000</td>
</tr>
<tr>
<td>Slow</td>
<td>100000</td>
<td>80000</td>
<td>66000</td>
<td>57000</td>
<td>280000</td>
<td>21000</td>
<td>16000</td>
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<td>10000</td>
<td>6000</td>
<td>4000</td>
<td>2500</td>
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<tr>
<td>Extra Slow</td>
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<td>16000</td>
<td>12000</td>
<td>10000</td>
<td>6000</td>
<td>4000</td>
<td>2500</td>
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</table>

Working Properties

Notes:
*Due to the thixotropic and filled nature of this system, these values are only indicative.

For an explanation of test methods used see ‘Formulated Products Technical Characteristics’.

All figures quoted are indicative of the properties of the product concerned. Some batch to batch variation may occur.

† All times are measured from when resin and hardener are first mixed together.
Working Properties (cont’d)

Sag Resistance

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>Temperature (°C)</th>
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<td>15</td>
<td>100</td>
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<td>153</td>
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<td>25</td>
<td>100</td>
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<tr>
<td>30</td>
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<table>
<thead>
<tr>
<th>Temperature (°C)</th>
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<td>15</td>
<td>Slow &amp; Extra Slow</td>
</tr>
<tr>
<td>20</td>
<td>Fast</td>
</tr>
<tr>
<td>25</td>
<td>Slow</td>
</tr>
<tr>
<td>30</td>
<td>Slow Extra Slow</td>
</tr>
</tbody>
</table>

Mechanical Properties

Glass Transition Temperature

Temperature (°C) vs. Time

28 days @ 21°C, 24 hrs @ 21°C +16 hrs @ 50°C, 5 hrs @ 70°C

Peak Tan, Ultimate Peak Tan

Cleavage Strength

Cleavage Strength (kN) vs. Time

28 days @ 21°C, 24 hrs @ 21°C +16 hrs @ 50°C, 5 hrs @ 70°C

Shear Strength on Shotblasted Steel

Shear Strength (MPa) vs. Time

28 days @ 21°C, 24 hrs @ 21°C +16 hrs @ 50°C, 5 hrs @ 70°C

Dry, After Water Exposure
Health and Safety

The following points must be considered:

1. Skin contact must be avoided by wearing protective gloves. SP-High Modulus recommends the use of disposable nitrile gloves for most applications. The use of barrier creams is not recommended, but to preserve skin condition a moisturising cream should be used after washing.

2. Overalls or other protective clothing should be worn when mixing, laminating or sanding. Contaminated work clothes should be thoroughly cleaned before re-use.

3. Eye protection should be worn if there is a risk of resin, hardener, solvent or dust entering the eyes. If this occurs flush the eye with water for 15 minutes, holding the eyelid open, and seek medical attention.

4. Ensure adequate ventilation in work areas. Respiratory protection should be worn if there is insufficient ventilation. Solvent vapours should not be inhaled as they can cause dizziness, headaches, loss of consciousness and can have long term health effects.

5. If the skin becomes contaminated, then the area must be immediately cleansed. The use of resin-removing cleansers is recommended. To finish, wash with soap and warm water. The use of solvents on the skin to remove resins etc must be avoided.

Washing should be part of routine practice:

- before eating or drinking
- before smoking
- before using the lavatory
- after finishing work

6. The inhalation of sanding dust should be avoided and if it settles on the skin then it should be washed off. After more extensive sanding operations a shower/bath and hair wash is advised.

SP-High Modulus produces a separate full Material Safety Data Sheet for all hazardous products. Please ensure that you have the correct MSDS to hand for the materials you are using before commencing work. A more detailed guide for the safe use of SP resin systems is also available from SP-High Modulus, and can be found at www.gurit.com

Applicable Risk & Safety Phrases

Resin
R 36/38, 43, 51/53
S 24, 26, 28, 37/39, 57, 60

Fast Hardener
R 20/21/22, 34, 43, 52/53, 62, 63, 68
S 9, 20, 26, 36/37/39, 45, 57

Slow Hardener
R 22, 35, 43
S 20, 26, 36/37/39, 43, 45, 60

Extra Slow Hardener
R 22, 35, 43
S 20, 26, 36/37/39, 43, 45, 60
Transport & Storage
The resin and hardeners should be kept in securely closed containers during transport and storage. Any accidental spillage should be soaked up with sand, sawdust, cotton waste or any other absorbent material. The area should then be washed clean (see appropriate Safety Data Sheet).

Adequate long term storage conditions will result in a shelf life of two years for both the resin and hardeners. Storage should be in a warm dry place out of direct sunlight and protected from frost. The temperature should be between 10°C and 25°C. Containers should be firmly closed. Hardeners, in particular, will suffer serious degradation if left exposed to air.

Notice
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The Company strongly recommends that Customers make test panels and conduct appropriate testing of any goods or materials supplied by the Company to ensure that they are suitable for the Customer’s planned application. Such testing should include testing under conditions as close as possible to those to which the final component may be subjected. The Company specifically excludes any warranty of fitness for purpose of the goods other than as set out in writing by the Company. The Company reserves the right to change specifications and prices without notice and Customers should satisfy themselves that information relied on by the Customer is that which is currently published by the Company on its website. Any queries may be addressed to the Technical Services Department.

Gurit are continuously reviewing and updating literature. Please ensure that you have the current version, by contacting Gurit Marketing Communications or your sales contact and
Appendix C

Material specifications for Weld-on SS620
DESCRIPTION
IPS WELD-ON® SS600 Series methacrylate adhesives are two-component, 10:1 mix ratio products for bonding thermoplastics, composites and metals. Minimal surface preparation is required on most composites and plastics\(^1,2\). Parts can be cross-bonded with metals. Packaging options include 490 ml cartridges and 5 or 50-gallon bulk containers for application with meter-mix dispensing equipment.

PERFORMANCE HIGHLIGHTS
• Choice of 5, 10 and 17 minute open times
• Minimal surface preparation\(^1,2\)
• Non-sag application characteristics
• Permanent toughness and high elongation
• Excellent flow characteristics

BENEFITS
Selection to fit application and process requirements
Reduced labor cost and throughput times
Facilitates application on non-level surfaces
Excellent fatigue, impact and shock load resistance
High flow at low pressure, improved flow rate

TYPICAL ADHESIVE CHARACTERISTICS @ 75°F (24°C)

<table>
<thead>
<tr>
<th></th>
<th>Part A Adhesive</th>
<th>Part B (SS605B) Activator</th>
<th>Mixed A+B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color:</td>
<td>Off White</td>
<td>Black</td>
<td>Black(^5)</td>
</tr>
<tr>
<td>Mix ratio by volume:</td>
<td>10</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Mix ratio by weight:</td>
<td>8.44</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Viscosity, cps:</td>
<td>150,000 - 200,000</td>
<td>80,000 - 120,000</td>
<td></td>
</tr>
<tr>
<td>Density, grams/ml:</td>
<td>0.97</td>
<td>1.15</td>
<td>0.99</td>
</tr>
<tr>
<td>Unit weight, lb/gallon:</td>
<td>8.10</td>
<td>9.60</td>
<td>8.24</td>
</tr>
</tbody>
</table>

TYPICAL PHYSICAL PROPERTIES @ 75°F (24°C)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength psi (mpa)</td>
<td>2,600 - 3,000 (18 - 21)</td>
</tr>
<tr>
<td>Maximum Tensile Elongation (%)</td>
<td>&gt;140</td>
</tr>
<tr>
<td>Modulus psi(^1) (mpa)</td>
<td>60,000 - 75,000 (413 - 517)</td>
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<tr>
<td>Lap Shear Strength(^1) psi (mpa)</td>
<td>2,700 - 3,200 (19 - 22)</td>
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<tr>
<td>Service Temperature, °F (°C)</td>
<td>-40 to 180 (-40 to 82)</td>
</tr>
</tbody>
</table>

RECOMMENDED SUBSTRATES
Acrylics
PVC, ABS
Vinylester
Coated Metals
Polyester Gelcoat
Aluminum\(^2\)
Other Thermoplastics
Steel\(^2\)

Bonds are generally resistant to the effects of heat, water and moisture, aqueous chemicals and most petroleum hydrocarbons, including gasoline, motor oil and diesel fuel. Not recommended for immersion or long-term exposure to concentrated acids or bases, or aggressive organic solvents such as toluene, ketones, and esters. User must determine the suitability of each adhesive for its intended use and application.

1. Most thermoplastics can be bonded with no surface preparation other than a dry wipe or air blow-off. If contamination is visible or suspected, wipe with alcohol prior to bonding. Polyolefins, thermoplastic polyesters, fluorocarbon plastics and other low surface energy plastics are generally not bondable. Testing is required on thermoset plastics due to variations in bondability. See important notes a, b, and c on reverse side.

2. Prepare metal for bonding by removing all dust, loose scale, rust, and other surface residue including oil and grease. Use of MP100 metal primer is a necessity and strongly recommended for stainless steel and aluminum bonding. Heavy grinding or sanding may interfere with the chemical action of MP100 and is not recommended, especially with aluminum and stainless steel. For maximum bond strength on steel, abrade the mating surfaces prior to bonding. See notes a, b and c on reverse side. Value will depend on strength and stiffness of substrate.

3. Modulus as measured in the linear portion of the stress/strain curve.

4. Lap shear strength for primed aluminum to aluminum bond based on ASTM D 1002.

5. Primary cured adhesive color of products offered in cartridges. Other colors are possible with products sold in bulk. Physical properties may vary slightly.

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SS600 PRODUCT PROPERTIES @ 75°F (24°C)

<table>
<thead>
<tr>
<th>Adhesive / Activator</th>
<th>Working Time Minutes</th>
<th>Fixture Time Minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS605 (SS605A / SS605B)</td>
<td>4 - 6</td>
<td>&gt;15</td>
</tr>
<tr>
<td>SS610 (SS610A / SS605B)</td>
<td>8 - 12</td>
<td>&gt;25</td>
</tr>
<tr>
<td>SS620 (SS620A / SS605B)</td>
<td>15 - 20</td>
<td>&gt;35</td>
</tr>
</tbody>
</table>

SAFETY AND HANDLING

Read Material Safety Data Sheet before handling or using this product. Adhesive component A contains methyl methacrylate monomer and is flammable. Always use in a well-ventilated area. Floor-level extraction and large quantities of moving air greatly facilitate ventilation. Activator component B contains peroxide. Both materials must be stored in a cool place away from sources of heat and open flames or sparks. Keep containers closed when not in use. Prevent contact with skin and eyes. In case of skin contact, wash with soap and water. In case of eye contact, flush with water for 15 minutes and seek immediate medical attention. Harmful if swallowed. Keep out of reach of children.

MIXING AND APPLICATION

EXOTHERM: The chemical curing reaction that occurs when components A and B are mixed generates heat. The amount of heat generated is controlled by the mass and thickness of the mixed product. Large masses over 1/2 inch thick can develop heat in excess of 250°F/121°C and can generate harmful, flammable vapors. Large curing masses should be carefully moved to a well-ventilated area where the chance of personal contact is minimized.

CURING: Open working time is the approximate time after mixing components A and B that the adhesive remains fluid and bondable. Fixture time is the approximate time after mixing components A and B required for the adhesive to develop sufficient strength to allow careful movement, unclamping or de-molding of assembled parts. Parts can generally be put in service when 80 percent of full strength is developed. The time to achieve 80% cure is approximately 2-3 times that required for fixture. The working and fixture times presented in this bulletin are based on laboratory tests performed at 75°F/24°C. Higher temperatures speed the curing reaction, which reduces open working time and speeds the development of strength. The reverse is true for lower temperatures. If significant variation in temperatures or application at very high or low temperatures is anticipated, contact your IPS representative for technical assistance.

DISPENSING EQUIPMENT: Dispensing directly from disposable cartridges or meter-mix-dispensing equipment is strongly recommended. Both methods employ convenient static motionless mixer technology. Product supplied in pre-measured cartridges is dispensed from approved manual or pneumatic powered guns. Contact your IPS representative for information and availability.

When meter-mix dispense systems are used, care must be taken to assure compatibility between the adhesive components and the materials in the equipment that they contact. All wetted metal components should be constructed of stainless steel or aluminum or have a sufficient thickness of chemically resistant material that prevents contact between the adhesive components and the base metal. Contact with copper, zinc, brass or other alloys containing these materials must be strictly prevented. All non-metallic seals and gaskets should be fabricated from Teflon® or UHMW polyethylene based materials. Natural rubber, nitrile rubber (BUNA), neoprene and Viton® are not acceptable. Ethylene-propylene rubbers, such as Nordel® may be used for ram follower plate o-rings, but a polyethylene sheet must be used to prevent direct contact with the adhesive.

APPLICATION: Follow instructions provided or contact your IPS representative for proper preparation of dispensing equipment and substrates prior to starting the bonding process. Always dispense a quantity of adhesive at start-up to assure that the adhesive exiting the tip of the mixer is the proper color and is uniform, without streaks. If previously opened or aged material is being used, allow the purged material to cure to assure quality before proceeding. Carefully dispense a sufficient quantity of adhesive on the substrate to assure that the bond gap will be completely filled when the parts are mated. Allow for squeeze-out at the edges of the bond to assure filling. Carefully secure or clamp parts to prevent joint movement while the adhesive sets. Do not apply excessive pressure that can cause excessively thin gaps and starve the bond line. If in doubt, use shims or spacers to set the gap. A minimum gap of 20 mils (0.020 inch) is recommended for these products. Test the curing adhesive at the edges for fingernail hardness before removing clamps or fixtures. If clean up of the adhesive from the bonded area is required, carefully wipe with alcohol or other preferred industrial solvent while the adhesive is still wet or soft, taking care not to disturb or move the mated parts. Partially cured adhesive can be carefully removed with a sharp knife. Cured adhesive must be sanded or scraped, using a suitable solvent to remove remaining traces.

CLEAN UP: Adhesive components and mixed adhesive should be removed from mixing equipment and application equipment with a suitable industrial solvent or cleaner before the mixed adhesive cures. Once the adhesive cures, soaking in a strong solvent or paint remover will be required to soften the adhesive for removal. If the bonds are exposed to UV rays then use of plasticizers such as Benzoflex 2088 is recommended, or contact your IPS representative for additional information. Any clean-up of the bonded assembly using industrial solvents is not recommended as it could affect the cure.

STORAGE AND SHELF LIFE

The shelf life of components A and B in unopened containers is approximately six months from the date the product is shipped from IPS facilities. Shelf life is based on steady state storage between 55°F and 80°F (13°C and 27°C). Exposure, intermittent or prolonged, above 80°F (27°C) will result in a reduction of the stored shelf life. Exposures above 100°F (38°C) during shipping or storage can quickly degrade component B in cartridges or bulk containers, and must be prevented. Shelf life of both components can be extended by air-conditioned or refrigerated storage between 50°F and 65°F (10°C and 18°C). KEEP FROM FREEZING.

IMPORTANT NOTES

a. SUBSTRATE AND APPLICATION COMPATIBILITY. The user must determine the suitability of a selected adhesive for a given substrate and application. IPS strongly recommends laboratory, shop and end-use testing that simulates the actual manufacturing and end-use environment.

b. SURFACE PREPARATION. The need for surface preparation must be determined by comparative testing of prepared and unprepared substrates to assure that unprepared bonding is equivalent to or acceptable for the application relative to prepared bonding. Initial bonding tests must be followed up with simulated or actual durability tests to assure that surface conditions do not lead to degradation of the bond over time under service conditions. Subsequent changes in substrates or bonding conditions will require re-testing.

c. TECHNICAL ASSISTANCE. Contact your IPS representative for questions or assistance with the selection of adhesives and methods for evaluating adhesives for your intended application.

This product is intended for use by skilled individuals at their own risk. Recommendations contained herein are based on information we believe to be reliable. The properties and strength values presented above are typical properties obtained under controlled conditions at the IPS laboratory. They are intended to be used only as a guide for selection for end-use evaluation. The ultimate suitability for any intended application must be verified by the end user under anticipated test conditions. Since specific use, materials and product handling are not controlled by IPS, our warranty is limited to the replacement of defective IPS products.

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Appendix D

Paper submitted to

CSCE conference (2011-Ottawa)
Bond between GFRP Plates and Structural Steel Members – An Experimental Investigation

Ramin Rameshni, Stefano Arcovio, Colin MacDougall
Department of Civil Engineering, Queen’s University, Canada

Abstract: Fibre reinforced polymer materials (FRPs) in the form of sheets and plates have been used for strengthening structural elements. Due to the high stiffness of steel, limited FRP applications for steel structures have been envisioned until just recently. Most of the research has been focused on increasing fatigue behaviour of such structures using these advanced materials. A campaign of research has been started recently to study the potential of using pultruded FRP profiles in splicing steel beams. Limited strength of the bond between FRP material and the original structure has been shown to be the main cause of failure for such applications. This is more dominant for the applications to steel structures. Thus, knowing the interfacial - both normal (peeling) and shear - stress distribution and comparing that to the specific strength of the adhesive used for the bond consists one of the main design criteria in this regard. Limited data is available for the behaviour of the adhesive bond between steel and FRP. Almost all the research on this subject has dealt with carbon fibre reinforced polymer (CFRP) and steel. Pultruded FRP sections available on the market are only made of GFRP. Due to limited data being available on the behaviour of the adhesive bond between steel and GFRP, the afore-mentioned study required, in its first stage, to explore this subject. This paper presents the results for two different adhesives, namely Spabond 345 and Weld-on SS620, between the above-mentioned adherends in a series of double-lap splice shear tests.

1. Introduction

Fibre reinforced polymer materials (FRPs) in the form of sheets and plates have been used for strengthening structural elements for more than two decades. Most applications have been in the field of concrete structures. However, interest in FRP application to steel structures has been recently increasing. In these applications the interfacial normal (peeling) and shear stresses often govern the failure.

Schnerch et al. (2004) investigated the bond quality of six different adhesives to be used between carbon FRP (CFRP) plates and steel beams under four-point bending. The best results, based on this research, come for Spabond 345 (epoxy-type adhesive) and Weld-on SS620 (methacrylate-type adhesive) with 76 and 102 mm development lengths, respectively. Schnerch et al. (2007) recommends Spabond 345 as the best adhesive for CFRP application. This epoxy has been used by Howard (2006), Fam et al. (2009), and Rameshni et al. (2010). Limited data could be found in literature for the bond between glass FRP (GFRP) material and steel. El Damatty et al. (2003) tested eight different adhesives and recommends a methacrylate type adhesive (MA 420) as the best one for GFRP to steel applications. It is noteworthy though that neither the full, detailed specifications nor the mechanical properties of all the adhesives examined in this study are given. The comparison between the test results for different adhesives being used is not provided either. As such, a comparison between these results and those drawn by other researchers is difficult.
Based on the limited data in the literature, the current study aims to identify the bond quality of two different adhesives, namely Spabond 345 (Adhesive A) and Weld-on SS620 (Adhesive B), between GFRP and steel as the adherends in a series of double-lap splice shear tests.

2. Experimental Work

In the first stage of this study, a total of eight (8) double-lap shear splice specimens were tested to failure. The effect of three parameters, namely bond length, method of bond surface preparation, and the adhesive type, were investigated.

2.1 Material

Each specimen consisted of two steel plates connected by two GFRP plates, one on each side, as shown in Figure 1. A 10 mm gap is provided between steel plates.

Steel plates were made of hot-rolled steel with a nominal yielding stress of 345 MPa and modulus of elasticity equal to 200 GPa. They were cut 70 mm wide by 12 mm thick into three different lengths, namely 210, 310, and 560 mm. These lengths are 115 mm greater than the desired bond length to provide enough space on each side to be gripped by the testing machine.

GFRP plates were cut from GFRP, square tube, pultruded sections made by Bedford Reinforced Plastics, Inc. The wall of the 10 mm thick section, which was used in this experimental study, contained 6 layers of randomly oriented, continuous E-glass filament mat (1½ oz; Type M-8643) with longitudinal, continuous E-glass roving (Type 366-113 (4400 TEX)) in between each layer of mat. Both mat and roving layers are provided by Owens Corning and wetted with isophthalic polyester resin (Type Aropol 2036-C). Polyester surfacing veils (Nexus 111-10) are provided on either side. The glass fibre volume fraction was 50%. Based on manufacturer’s data (Bedford Reinforced Plastics Inc.: Design Guide), the ultimate strength and modulus of elasticity, in the direction of the fibres, are 206.8 MPa and 17.2 GPa respectively (ASTM D638). The GFRP plates were cut using a diamond blade saw in sections 50 mm wide by three different lengths: 200, 400, and 900 mm.

Adhesive A is an epoxy adhesive made by Gurit (UK) Ltd. The mixing ratio of resin to hardener is 2:1 by volume. A fast hardener was used to reduce the clamping time. The cleavage strength of the cured epoxy is 12.35 kN. This is equal to 33 MPa for tensile strength according to ASTM D 1062-08. The shear strength of the epoxy is 36.6 MPa (Gurit (UK) Ltd: Spabond 345 Epoxy Adhesive System).
Adhesive B is a methacrylate two-component adhesive made by IPS Structural Adhesives, Inc. The mixing ratio of adhesive (Part A) to activator (Part B; SS605B) is 10:1 (by volume). It has a nominal tensile strength of 18-21 MPa and lap shear strength of 19-22 MPa, based on the manufacturer's technical data sheet.

2.2 Fabrication of test specimens

For each test specimen, two steel plates, sandblasted on each side using the grit specifications as suggested by Schnerch et al. (2007), were aligned longitudinally using wood blocks. The bond area on the steel plates was marked and the grip area covered by duct tape to remain clean. The longitudinal centrelines of both steel and GFRP plates were also marked (Figure 2.b).

In the next step, the steel bond surface was washed off with acetone and dried using air pressure. The GFRP bond surface was cleaned using Isopropanol 99%. The adhesive was applied uniformly to both surfaces. In order to avoid any air voids trapped in the bond, the adhesive was applied in a triangular form so that more epoxy was on the centreline. Using a roller, a constant pressure was applied to the GFRP plate from centre of specimen to its corners to force any trapped air to exit from between the adherends. E-glass spacer beads of 0.8 mm diameters were applied to the bond surfaces to ensure an optimum bond thickness of 1-2 mm (Schnerch et al. 2007). The GFRP plates were held in place for the minimum required setting time of the adhesive. Then, the wood blocks were removed and more adhesive was applied to the edges in a fillet form (Figure 2.c). The specimen was left in place for a minimum of 24 hours in lab temperature before the same procedure was done for the other side of the specimen. For the adhesive A, the specimen was cured at 50 ºC for a minimum of 16 hours to reach its nominal strength in a short span of time, as advised by the manufacturer. Minimum 24 hours in the lab temperature, on the other hand, was sufficient for the adhesive B to reach its nominal strength as stated by the manufacturer.

Figure 2: a) GFRP bond surface sandblasted; b) Steel bond surface sandblasted and marked; c) GFRP bonded to steel on one side
Table 1 is the test matrix. For two specimens, S1 and S2, the bond surface on the steel side was sandblasted using the grit specifications provided by Schnerch et al. (2007). The bond surface on the GFRP plate, however, was only hand-abraded using a #120 sandpaper. The test results for these specimens showed formation of premature crack and weak bonds between adhesive and adherends, as will be discussed later. As such, for the other six specimens an enhanced preparation method was used: The bond surface of GFRP plates was sandblasted using the same grit specifications used for steel (Figure 2.a) and in order to enhance the bond between steel and adhesive some diagonal narrow grooves (less than 2 mm deep) were created at a 45º angle with respect to the longitudinal axis, using a hand grinder, before being sand blasted as recommended by Schnerch et al. 2007. The resulting failure mode, as will be seen later, was consistently a delamination through the FRP section.

2.3 Test set-up and instrumentation

All specimens were tested using a 250 kN Instron testing machine. Load was applied using a stroke control at a rate of 0.3 mm/min. One strain gage, mounted at the midheight of the specimen, was used to read the maximum strain in GFRP at failure. Load, stroke, and midheight strain were recorded.

3. Results

Figures 3.a & b show the effect of different bond surface preparation methods on the load-stroke response of the specimens. For both adhesives, the enhanced preparation method used for the bond surfaces, i.e. creating diagonal narrow grooves in steel plus sandblasting both steel and GFRP surfaces, resulted in the elimination of premature cracks. For specimen S4, the stroke reading towards the end of testing encountered unexpected noise. This was believed to be due to some internal problem for the testing machine. Nevertheless, the initial part of the load-stroke diagram for this specimen, showed no evidence of premature cracks, and is in complete agreement with the results yielded for specimens S1 and S7 where the adhesive A was used. Although the behaviour of the bond for both preparation methods being used, other than what already mentioned, is more or less the same, different failure modes have been noticed when different preparation methods were used as will discussed later.

Another advantage of applying the enhanced method of preparation for bond surface, as shown in Figures 4.a & b, is stress more uniformly being transferred between adherends such that the maximum strain reading in GFRP at midheight is higher for the specimens where the enhanced preparation method was used (i.e. S4 and S7).

Figures 5.a & b show the effect of bond length on load-stroke response of the specimens for both adhesives being used. For both adhesives, maximum capacity occurs when an intermediate bond length (195 mm) has been used. The next in the rank, however, is not the same for different adhesives being used. For the adhesive A, the 445 mm bond length results in second ranked shear capacity whereas this bond length showed the minimum shear capacity when the adhesive B was used.
Figure 3: Load vs. stroke for different bond surface preparation: (a) Adhesive A; (b) Adhesive B

Figure 4: Load vs. strain for different bond surface preparation: (a) Adhesive A; (b) Adhesive B

Figure 5: Load vs. stroke for different bond lengths: (a) Adhesive A; (b) Adhesive B
As the bond length increases, specimens made by both adhesives show less initial stiffness. The change in stiffness, however, is not proportional to the bond length. The most severe difference, when the adhesive A is used, is between the shortest and intermediate bond length. For the adhesive B, though, this happens going from intermediate to the longest bond length. The difference in initial stiffness between the shortest and longest bond length, however, is similar for both adhesives (around 25%).

For the adhesive A, the highest ductility happens when the longest bond length is used.

The midheight strain vs. load has been compared, for different bond lengths and the adhesives used, in Figures 6.a & b. Similarly for both adhesives, the maximum strain in the GFRP plate happens when an intermediate bond length (i.e. 195 mm) was used. This is more dominant when the adhesive B was used. The load-midheight strain response of the specimens using the adhesive B is also showing a more consistent pattern. This means that this adhesive shows a less brittle behaviour under loading.

Figures 7.a-c illustrate the effect of different adhesives being used on the load-stroke response of the specimens. As evident from these figures, using the adhesive B instead of the adhesive A not only enhanced the shear capacity of the bond but also increased the ductility of the bond. The shorter the bond length is, the more dominant the increase in the shear capacity of the bond. The increase in the shear bond capacity ranges from \( \geq 40\% \) for the 95 mm bond length to \( \leq 10\% \) for the 445 mm one.

Load-midheight strain responses of the specimens, made by different adhesives, have been compared in Figures 8.a-c. Again, these diagrams show a less brittle behaviour for the adhesive B. Despite being less stiff, and also having lower strength, the higher ductility of the adhesive B has a great advantage on the overall behaviour of the bond. Not only has the shear capacity of the bond been increased, as already mentioned, but also the stress transferring functionality of the bond has been fulfilled much better, so that at a certain level of loading, the available strain and as a result the stress, in GFRP section is higher for the case the adhesive B is used. This effect is more noticeable for shorter bond lengths.

Figure 6: Load vs. strain for different bond lengths: (a) Adhesive A; (b) Adhesive B
Figure 8: Load vs. stroke for different adhesives: (a) BL=95 mm; (b) BL=195 mm; (c) BL=445 mm

Figure 7: Load vs. strain for different adhesives: (a) BL=95 mm; (b) BL=195 mm; (c) BL=445 mm
4. Discussion

A total of eight specimens were tested under double-lap splice shear tests to study the effect of three factors, namely bond surface preparation method, bond length, and adhesive type, on shear bond capacity between GFRP material and steel. The failure modes observed for the specimens tested in this study (Table 1) could be categorized into four groups, as follows:

**Group 1:** Premature debonding between adhesive and one of the adherends (Shear failure).

**Group 2:** Delamination through the GFRP thickness (Shear failure).

**Group 3:** Delamination through GFRP thickness on one side plus debonding between adhesive and adherend on the other side (shear failure).

**Group 4:** Delamination through GFRP thickness on one side (shear failure), plus debonding between adhesive and adherend on the other side (due to bending).

Failure mode Group 1 happened in the specimens using the ordinary preparation method for the bond surfaces (S1 & S2). As a result, the bond created between adhesive and adherends were of a weaker strength.

Failure mode Groups 2 and 3 happened indifferently for the specimens using the enhanced method of bond surface preparation.

Failure mode Group 4 happened for S5 and S8, the specimens with longest bond length made using the adhesive B. In the authors' opinion, the imperfections involved in making a long specimen like this may have resulted in a tensile buckling after the initial cracks happened. This might have increased the rate of failure for these specimens, which explains why they have not reached the capacity of specimens with the intermediate bond length.

Nevertheless, this significant reduction in bond strength capacity, when bending is available in addition to pure shear (the simultaneous effect of available peeling and shear stresses in bond), clearly shows the importance of considering the simultaneous effect of these two types of stresses when they are both available (e.g. when FRP plates are being used for strengthening beams under bending).

The failure line happened to be either of a U shape (Figure 9.a) or S shape (Figure 9.b). It is, though, of no significant importance in the authors' opinion, as neither of these two failure paths has any preference for a sample with this configuration. What matters though, is that the failure always happened through both sides of the specimens which implies consistent quality of the bond for two sides.

The methacrylate adhesive (B) shows overall more shear bond capacity compared to the epoxy adhesive (A) when being used for GFRP and steel. This is in agreement with results gained by El Damatty et al. (2003). It could be partly attributed to a more ductile behaviour of the adhesive B, although the observance of the failure patterns for the specimens shows that this type of adhesive (methacrylate) creates a better bond with GFRP than steel. All the debonding failures for the specimens using this type of adhesive fell at the interface of steel and adhesive. This is the other way around for the epoxy adhesive (A) where all the debonding happened between GFRP and adhesive, especially when the bond between steel and adhesive enhanced by creating the narrow 45° grooves.

5. Conclusion

This study was performed to quantify the effect of three factors, namely bond surface preparation method, bond length, and adhesive type, on the behaviour of adhesive bonds between steel and GFRP material. The conclusions of this study are:
1. The methacrylate adhesive (B) creates a better bond (up to 40%) with GFRP compared to the epoxy one (A). It also shows a more ductile (up to 100%) behaviour which is crucial for fatigue purposes.

2. An enhanced method of preparation for bond surfaces, including sandblasting both adherends’ surfaces and introducing some 45° narrow grooves into steel before sandblasting, is necessary to avoid premature debonding failure.

3. Despite having less specific mechanical properties, the methacrylate adhesive (B) results in a higher bond capacity compared to the epoxy one (A).

4. Increasing bond length results in an increased bond capacity and a more ductile behaviour. Nevertheless, for a too long bond length, inclusion of unavoidable manufacturing imperfections results in simultaneous shear/bending failure modes which causes a significant reduction in capacity (~ 40%). This highlights the significant role of the synergistic effect of peeling/shear stresses where both are available.

6. Acknowledgements

The authors would like to thank Gurit (UK) Ltd. for its generous donation of the Spabond 345 (Adhesive A) required for the purpose of this study.

Figure 9: Failure modes: (a) Group 2 - U shape; (b) Group 3 - S shape; (c) Group 4
7. References


Rameshni, R., MacDougall, C., and Green, M. F. 2010. Hybrid Steel/FRP Field Splices for Expansion Joints, *Proceedings of 8th International Conference on Short and Medium Span Bridges*, Canadian Society for Civil Engineering, Niagara Falls, Ontario, Canada


Appendix $E$

Tensile coupon test results for

Weld-on SS620
ASTM D638-Tensile Properties of Plastics

Customer
Adhesive/Activator
Operator
Lab Book Number
Number of specimens in sample
Post cure
Temperature
Humidity
Specimen treatment

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>Maximum Load (lbf)</th>
<th>Max Tensile Stress (psi)</th>
<th>Tensile Strain (%)</th>
<th>Tensile Strain (%)</th>
<th>Extension at Break (in)</th>
<th>Secant Modulus (psi)</th>
<th>Thickness (in)</th>
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<td>3142.33</td>
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<tr>
<td>Mean</td>
<td>79.76</td>
<td>3185.08</td>
<td>45.969</td>
<td>46.00</td>
<td>0.92</td>
<td>142923.12</td>
<td>0.101</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>2.68</td>
<td>82.49</td>
<td>14.06</td>
<td>14.07</td>
<td>0.28</td>
<td>11756.86</td>
<td>0.00</td>
</tr>
<tr>
<td>Minimum</td>
<td>75.99</td>
<td>3107.62</td>
<td>31.208</td>
<td>31.24</td>
<td>0.62</td>
<td>134507.70</td>
<td>0.099</td>
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<tr>
<td>Maximum</td>
<td>82.25</td>
<td>3296.96</td>
<td>63.396</td>
<td>63.43</td>
<td>1.27</td>
<td>160315.05</td>
<td>0.103</td>
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<tr>
<td>Range</td>
<td>6.26</td>
<td>189.34</td>
<td>32.188</td>
<td>32.19</td>
<td>0.64</td>
<td>25807.35</td>
<td>0.004</td>
</tr>
</tbody>
</table>
Appendix $F$

Technical specifications of

Novotechnik LPs (TRS series)
Position Transducers
with Restoring Spring
10, 25, 50, 75, 100 mm

TR, TRS Series

Special features
• long life – 100 x 10^6 movements
• outstanding linearity – up to ±0.075%
• choice of plug or cable connection
• DIN standard gauging end
• double bearing system on shaft
• insensitive to shock and vibration
• Repeatability to ±0.002 mm

Position sensors employing conductive-plastic resistance and collector tracks provide direct means of measuring position or profile, without the need of a solid mechanical coupling.

One important feature of the TR, TRS Series is the industry proven double-bearing systems on both actuator shaft and spring. This arrangement reduces side load errors that could occur in an application such as cam-following and is one of the design factors that enables the outstanding linearity of this series.

The back end of the actuator shaft has a special collar that allows the attachment of an air cylinder of solenoid to automatically retract the actuator when required.

Table:

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Housing</td>
<td>aluminum, anodized</td>
</tr>
<tr>
<td>Actuating shaft</td>
<td>stainless steel with anti-rotation device, inside thread M 2.5 x 6</td>
</tr>
<tr>
<td>Fixings</td>
<td>adjustable clamps</td>
</tr>
<tr>
<td>Gauging head</td>
<td>stainless steel with external M 2.5 thread and hardened ball point</td>
</tr>
<tr>
<td>Bearings</td>
<td>both ends in DU plastic bearings</td>
</tr>
<tr>
<td>Resistance element</td>
<td>conductive plastic</td>
</tr>
<tr>
<td>Wiper assembly</td>
<td>precious metal multi-finger wiper, elastomer-damped</td>
</tr>
<tr>
<td>Electrical connections</td>
<td>type TR, type TRS</td>
</tr>
<tr>
<td>type TR</td>
<td>three conductor stress-relieved, shielded cable, 2 m plug connector</td>
</tr>
</tbody>
</table>
Type designations | TR 10 | TR 25 | TR 50 | TR 75 | TR 100 | with cable | with plug
---|---|---|---|---|---|---|---
Electrical Data
Defined electrical range | 10 | 25 | 50 | 75 | 100 | mm | mm
Nominal resistance | 1 | 1 | 5 | 5 | 5 | kΩ | kΩ
Resistance tolerance | 20 | ±% | ±% | ±% | ±% | ±% | ±%
Independent linearity | 0.25 | 0.2 | 0.15 | 0.1 | 0.075 | ±% | ±%
Repeatability | 0.002 | mm | mm | mm | mm | mm | mm
Recommended operating wiper current | ≤ 1 | μA | μA | μA | μA | μA | μA
Max. wiper current in case of malfunction | 10 | mA | mA | mA | mA | mA | mA
Max. permissible applied voltage | 24 | 42 | 42 | 42 | 42 | V | V
Effective temperature coefficient of the output-to-applied voltage ratio | typical 5 | ppm/K | ppm/K | ppm/K | ppm/K | ppm/K | ppm/K
Insulation resistance (500 VDC, 1 bar, 2 s) | ≥ 10 | MΩ | MΩ | MΩ | MΩ | MΩ | MΩ
Dielectric strength (50 Hz, 2 s, 1 bar, 500 VAC) | | ≤ 100 | μA | μA | μA | μA | μA
Mechanical Data
Overall length (dimension A) | 48 | 63 | 94.4 | 134.4 | 166 | +1 mm | +1 mm
Mechanical stroke (dimension B) | 15 | 30 | 55 | 80 | 106 | ±1.5 mm | ±1.5 mm
Dimension C (at TR) | 7 | 12 | 12 | 12 | 12 | mm | mm
Dimension D (at TR) | 6 | 32 | 32 | 32 | 32 | mm | mm
Weight with cable | 80 | 120 | 150 | 180 | 200 | g | g
Weight with plug | 74 | 100 | 128 | 150 | g | g
Weight of the actuating shaft with coupling and wiper block | 18 | 25 | 36 | 48 | 57 | g | g
Operating force (horizontal) | ≤ 5 | N | N | N | N | N | N
Operating frequency max. (in critical applications mount the transducer with the gauging head upwards) | 20 | 18 | 14 | 11 | 10 | Hz | Hz
Maximum permitted torque for fixing screws | 140 | Ncm | Ncm | Ncm | Ncm | Ncm | Ncm

Environmental Data
Temp. range -30...+100 °C
Vibration 5...2000 Hz, A_{max} = 0.75 mm, a_{max} = 20 g
Shock 50 g, 11 ms
Life > 100 x 10^6 movements
Protection class IP 40 (EN 400 50 / IEC 529)

Order designations
Type | Art. no.
---|---
TR 10 | 023260
TR 25 | 023261
TR 50 | 023262
TR 75 | 023263
TR 100 | 023264

Important
All values given for this series – including linearity, lifetime, micro-
linearity, resistance to external
disturbances and temperature
efficient in voltage dividing
mode – are quoted for the device
operating with the wiper voltage
driving an operational amplifier
working as a voltage follower
where virtually no load is applied
to the wiper (le <= 1 μA).

Included in delivery
2 fixing clamps Z 45 incl.
4 screws M4x10,
1 gauging head with hardened ball point

Recommended accessories
Plug type EEM 33-70, protection class IP 67
Plug type EEM 33-71, protection class IP 40
Plug type EEM 33-72, protection class IP 40
1 roller head Z 50
Process-controlled indicators MAP.../MUK... with display.
Signal conditioner MUP... for standardized output signals

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155 Northboro Road
Southborough, MA 01772
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Fax: 508-485-2430
Email: info@novotechnik.com

Subject to changes
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Appendix \( G \)

Technical specifications of

Vishay strain gauges
# General Purpose Strain Gages - Linear Pattern

## GAGE PATTERN DATA

<table>
<thead>
<tr>
<th>GAGE DESIGNATION</th>
<th>RESISTANCE (OHMS)</th>
<th>OPTIONS AVAILABLE</th>
</tr>
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<tbody>
<tr>
<td>L2A-XX-250LW-120</td>
<td>120 ± 0.6%</td>
<td></td>
</tr>
<tr>
<td>L2A-XX-250LW-350</td>
<td>350 ± 0.6%</td>
<td></td>
</tr>
<tr>
<td>C2A-XX-250LW-120</td>
<td>120 ± 0.6%</td>
<td></td>
</tr>
<tr>
<td>C2A-XX-250LW-350</td>
<td>350 ± 0.6%</td>
<td></td>
</tr>
</tbody>
</table>

**DESCRIPTION**

Widely used general-purpose gage.

---

## GAGE DIMENSIONS

<table>
<thead>
<tr>
<th>Legend</th>
<th>Gage Length</th>
<th>Overall Length</th>
<th>Grid Width</th>
<th>Overall Width</th>
<th>Matrix Length</th>
<th>Matrix Width</th>
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</thead>
<tbody>
<tr>
<td>S</td>
<td>0.250</td>
<td>0.363</td>
<td>0.100</td>
<td>0.100</td>
<td>0.440</td>
<td>0.170</td>
</tr>
<tr>
<td>M</td>
<td>6.35</td>
<td>9.22</td>
<td>2.54</td>
<td>2.54</td>
<td>11.18</td>
<td>4.32</td>
</tr>
</tbody>
</table>

**Legend**: ES = Each Section, CP = Complete Pattern, S = Section (S1 = Sec 1), M = Matrix

---

## GAGE SERIES DATA

<table>
<thead>
<tr>
<th>Series</th>
<th>Description</th>
<th>Strain Range</th>
<th>Temperature Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>L2A</td>
<td>Encapsulated constantan gages with preattached ribbon leads.</td>
<td>±3%</td>
<td>−100° to +250°F [-75° to +120°C]</td>
</tr>
<tr>
<td>C2A</td>
<td>Encapsulated constantan gages with preattached ready-to-use cables.</td>
<td>±3%</td>
<td>−60° to +180°F [-50° to +80°C]</td>
</tr>
</tbody>
</table>

---

**Note 1**: Insert desired S-T-C number in spaces marked XX.
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Appendix $H$

Standard installation process for

Vishay strain gauges
INTRODUCTION

Vishay Micro-Measurements Certified M-Bond 200 is an excellent general-purpose laboratory adhesive because of its fast room-temperature cure and ease of application. When properly handled and used with the appropriate strain gage, M-Bond 200 can be used for high-elongation tests in excess of 60,000 microstrain, for fatigue studies, and for one-cycle proof tests to over +200 °F [+95 °C] or below -300 °F [-185°C]. The normal operating temperature range is -25° to +150°F [-30° to +65°C]. M-Bond 200 is compatible with all Vishay Micro-Measurements strain gages and most common structural materials. When bonding to plastics, it should be noted that for best performance the adhesive flowout should be kept to a minimum. For best reliability, it should be applied to surfaces between the temperatures of +70° and +85°F [+20° to +30°C], and in a relative humidity environment of 30% to 65%.

M-Bond 200 catalyst has been specially formulated to control the reactivity rate of this adhesive. The catalyst should be used sparingly for best results. Excessive catalyst can contribute many problems; e.g., poor bond strength, age-embrittlement of the adhesive, poor glueline thickness control, extended solvent evaporation time requirements, etc.

Since M-Bond 200 bonds are weakened by exposure to high humidity, adequate protective coatings are essential. This adhesive will gradually become harder and more brittle with time, particularly if exposed to elevated temperatures. For these reasons, M-Bond 200 is not generally recommended for installations exceeding one or two years.

For proper results, the procedures and techniques presented here should be used with qualified Vishay Micro-Measurements installation accessory products (refer to Catalog A-110). Those used in this procedure are:

- CSM Degreaser or GC-6 Isopropyl Alcohol
- Silicon Carbide Paper
- M-Prep Conditioner A
- M-Prep Neutralizer 5A
- GSP-1 Gauze Sponges
- CSP-1 Cotton Applicators
- PCT- 2M Gage Installation Tape

SHELF AND STORAGE LIFE

M-Bond 200 adhesive has a shelf life of three months at +75°F [+24°C] after opening and with the cap placed back onto the bottle immediately after each use.

Note: To ensure the cap provides a proper seal, the bottle spout should be wiped clean and dry before replacing the cap.

Unopened M-Bond 200 adhesive may be stored up to three months at +75°F [+24°C] or six months at +40°F [+5°C].

HANDLING PRECAUTIONS

M-Bond 200 is a modified alkyl cyanoacrylate compound. Immediate bonding of eye, skin or mouth may result upon contact. Causes irritation. The user is cautioned to: (1) avoid contact with skin; (2) avoid prolonged or repeated breathing of vapors; and (3) use with adequate ventilation. For additional health and safety information, consult the Material Safety Data Sheet, which is available upon request.

Note: Condensation will rapidly degrade adhesive performance and shelf life; after refrigeration the adhesive must be allowed to reach room temperature before opening, and refrigeration after opening is not recommended.

GAGE APPLICATION TECHNIQUES

The installation procedure presented on the following pages is somewhat abbreviated and is intended only as a guide in achieving proper gage installation with M-Bond 200. Vishay Micro-Measurements Application Note B-129 presents recommended procedures for surface preparation, and lists specific considerations which are helpful when working with most common structural materials.
Step 1

Thoroughly degrease the gaging area with solvent, such as CSM Degreaser or GC-6 Isopropyl Alcohol. The former is preferred, but there are some materials (e.g., titanium and many plastics) that react with strong solvents. In these cases, GC-6 Isopropyl Alcohol should be considered. All degreasing should be done with uncontaminated solvents—thus the use of “one-way” containers, such as aerosol cans, is highly advisable.

Step 2

Preliminary dry abrading with 220- or 320-grit silicon-carbide paper is generally required if there is any surface scale or oxide. Final abrading is done by using 320-grit silicon-carbide paper on surfaces thoroughly wetted with M-Prep Conditioner A; this is followed by wiping dry with a gauze sponge. Repeat this wet abrading process with 400-grit silicon-carbide paper, then dry by slowly wiping through with a gauze sponge.

Using a 4H pencil (on aluminum) or a ballpoint pen (on steel), burnish (do not scribe) whatever alignment marks are needed on the specimen. Repeatedly apply M-Prep Conditioner A and scrub with cotton-tipped applicators until a clean tip is no longer discolored. Remove all residue and Conditioner by again slowly wiping through with a gauze sponge. Never allow any solution to dry on the surface because this invariably leaves a contaminating film and reduces chances of a good bond.

Step 3

Now apply a liberal amount of M-Prep Neutralizer 5A and scrub with a cotton-tipped applicator. With a single, slow wiping motion of a gauze sponge, carefully dry this surface. Do not wipe back and forth because this may allow contaminants to be redeposited.

Step 4

Using tweezers to remove the gage from the transparent envelope, place the gage (bonding side down) on a chemically clean glass plate or gage box surface. If a solder terminal will be used, position it on the plate adjacent to the gage as shown. A space of approximately 1/16 in [1.6 mm] or more where space allows or application requires should be left between the gage backing and terminal. Place a 4- to 6-in [100- to 150-mm] piece of Vishay Micro-Measurements PCT-2M gage installation tape over the gage and terminal. Take care to center the gage on the tape. Carefully lift the tape at a shallow angle (about 45 degrees to specimen surface), bringing the gage up with the tape as illustrated above.
Step 5

Position the gage/tape assembly so that the triangle alignment marks on the gage are over the layout lines on the specimen. If the assembly appears to be misaligned, lift one end of the tape at a shallow angle until the assembly is free of the specimen. Realign properly, and firmly anchor at least one end of the tape to the specimen. Realignment can be done without fear of contamination by the tape mastic if Vishay Micro-Measurements PCT-2M gage installation tape is used, because this tape will retain its mastic when removed.

Step 6

Lift the gage end of the tape assembly at a shallow angle to the specimen surface (about 45 degrees) until the gage and terminal are free of the specimen surface. Continue lifting the tape until it is free from the specimen approximately 1/2 in [10 mm] beyond the terminal. Tuck the loose end of the tape under and press to the specimen surface so that the gage and terminal lie flat, with the bonding surface exposed. **Note:** Vishay Micro-Measurements gages have been treated for optimum bonding conditions and require no pre-cleaning before use unless contaminated during handling. If contaminated, the back of any gage can be cleaned with a cotton-tipped applicator slightly moistened with M-Prep Neutralizer 5A.

Step 7

M-Bond 200 catalyst can now be applied to the bonding surface of the gage and terminal. M-Bond 200 adhesive will harden without the catalyst, but less quickly and reliably. Very little catalyst is needed, and it should be applied in a thin, uniform coat. Lift the brush-cap out of the catalyst bottle and wipe the brush approximately 10 strokes against the inside of the neck of the bottle to wring out most of the catalyst. Set the brush down on the gage and swab the gage backing. Do not stroke the brush in a painting style, but slide the brush over the entire gage surface and then the terminal. Move the brush to the adjacent tape area prior to lifting from the surface. Allow the catalyst to dry at least one minute under normal ambient conditions of +75°F [+24°C] and 30% to 65% relative humidity before proceeding.

**Note:** The next three steps must be completed in the sequence shown, within 3 to 5 seconds. Read Steps 8, 9, and 10 before proceeding.

Step 8

Lift the tucked-under tape end of the assembly, and, holding in the same position, apply one or two drops of M-Bond 200 adhesive at the fold formed by the junction of the tape and specimen surface. This adhesive application should be approximately 1/2 in [13 mm] outside the actual gage installation area. This will insure that local polymerization that takes place when the adhesive comes in contact with the specimen surface will not cause unevenness in the gage glueline.
Step 9

Immediately rotate the tape to approximately a 30-degree angle so that the gage is bridged over the installation area. While holding the tape slightly taut, slowly and firmly make a single wiping stroke over the gage/tape assembly with a piece of gauze bringing the gage back down over the alignment marks on the specimen. Use a firm pressure with your fingers when wiping over the gage. A very thin, uniform layer of adhesive is desired for optimum bond performance.

Step 10

Immediately upon completion of wipe-out of the adhesive, firm thumb pressure must be applied to the gage and terminal area. This pressure should be held for at least one minute. In low-humidity conditions (below 30%), or if the ambient temperature is below +70°F [+20°C], this pressure application time may have to be extended to several minutes.

Where large gages are involved, or where curved surfaces such as fillets are encountered, it may be advantageous to use preformed pressure padding during the operation. Pressure-application time should again be extended due to the lack of “thumb heat” which helps to speed adhesive polymerization. Wait two minutes before removing tape.

Step 11

The gage and terminal strip are now solidly bonded in place. It is not necessary to remove the tape immediately after gage installation. The tape will offer mechanical protection for the grid surface and may be left in place until it is removed for gage wiring. To remove the tape, pull it back directly over itself, peeling it slowly and steadily off the surface. This technique will prevent possible lifting of the foil on open-faced gages or other damage to the installation.

FINAL INSTALLATION PROCEDURE

1. Referring to Vishay Micro-Measurements Catalog A-110, select appropriate solder and attach leadwires. Prior to any soldering operations, open-faced gage grids should be masked with PDT-1 drafting tape to prevent possible damage.

2. Remove the solder flux with Rosin Solvent, RSK-1.

3. Select and apply protective coating according to the protective coating selection chart found in Catalog A-110.
Appendix I

Technical drawings of

Fatigue test set-up
Length: 400 mm
HSS 152.152.13
\[ \tan(\theta) = 0.25 \]
\[
\tan(\theta) = 0.25
\]
<table>
<thead>
<tr>
<th>Material</th>
<th>Description</th>
<th>Req'd</th>
<th>Item No.</th>
<th>M62 bolts (A325)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td></td>
<td>20</td>
<td>M62</td>
<td>20</td>
</tr>
</tbody>
</table>

**RQRD:** 20

**nuts and washers**

**M20 bolts (A325) plus**
Appendix J

Fatigue test set-up

Final design

Ramin Rameshni
Queen’s University
February 2010
Farigue test set-up - Final design

The following assumptions were made:

- Two cases of the simultaneous application of a horizontal force equal to 25% and 50% of the applied vertical load were considered. These cases were simulated by tilting the specimen to the angles \( \Theta = 14^\circ \) and \( \Theta = 26.6^\circ \) respectively as shown in the following. The latter (\( \Theta = 26.6^\circ \)) was used to calculate the maximum design load.

- The maximum fatigue load range is 56 kN as per CHBDC 2006. To ensure that the produced tensile stresses never pass zero, a minimum applied load of 4 kN was considered. This complies with the provisions provided in NCHRP Report 402. Thus the maximum applied load in a fatigue
The design load was, thus, calculated to be 200 kN as follows:

\[ V = 60 \times 3 = 180 \text{ kN} \]
\[ H = 50\% \times V = 90 \text{ kN} \]
\[ R = \sqrt{V^2 + H^2} \approx 200 \text{ kN} \]

To satisfy design criteria, maximum principal stress (tensile) in each component, consisting the setup, is calculated and compared to the constant amplitude fatigue threshold for different categories as stated in CHBDC 2006 (e.g. \( F_{srt} = 165 \text{ MPa} \) for 'detail category A' or \( F_{srt} = 31 \text{ MPa} \) for 'detail category E').

- Elements (components) consisting the fatigue test set-up are labeled in the attached drawings.
- Stress analysis is done using finite element method and checked against approximate hand calculations.

(A.J. II)
Element A (H38 - 254 x 152 x 13)

(a) Finite Element Analysis:

- Loading is defined as constant displacements of the WT section (welded as the griphandle) equal to 200 kN.

- Interaction between the WT section and H38 section is introduced so that there would be no slip between them. This is assumed to be closest to the welded connection in practice.

- Both supports are introduced as ‘hinge’ over the perimeter of an area 254 x 100 mm equal to that of the washer used between nuts and H38 section (Element 0).

Results

Tensile stress: 120 MPa < 165 MPa  \( \text{OK!} \)

Results are shown graphically in the following pages.

A.1-208
(b) Approximate hand calculations (As a check)

\[ V = 500 \text{ kN} \]
\[ M = 550 \text{ mm} \]
\[ l_n = 550 \text{ mm} \]

**Worst case:**
\[ l_n = 450 + 2 \times 50 = 550 \text{ mm} \]

\[ V_{\text{max}} = 100 \text{ kN} \]
\[ M_{\text{max}} = 27.5 \text{ kN.m} \]

\[ S_{\text{yy}} = 4.42 \times 10^3 \times 50\% \]
\[ = 221 \times 10^3 \text{ mm}^3 \]

\[ t = \frac{M}{S} = \frac{27.5 \times 10^6}{221 \times 10^3} = 124 \text{ MPa} \]

**Check for bending:**

(Reduction factor assumed to account for the slots available)

**Check for shear and torsion:**

Due to the eccentricity of the reaction of test specimen with respect to the applied load (max. 50 mm), an effect of potential torsion equal to

\[ T = 200 \times \frac{50}{1000} = 10 \text{ kN.m} \]

has been considered.

\[ (A - J^{\text{2004}}) \]
\[
\sigma = \max \left\{ \frac{(V_{\text{ax}} + T/0.254) \times 10^3}{2 \times 152 \times 12.7}, \frac{(T/0.152) \times 10^3}{2 \times 254 \times 1.50 \times 12.7} \right\} = 36.1 \text{ MPa} \quad \text{Controls}
\]

(\* To account for the available slots)

For simplicity, the 3-D state of the concerned element could be assumed as a 2-D one:

Thus, the state of stress would be:

\[
\sigma_x = 124 \text{ MPa}, \quad \tau_{xy} = 36.1 \text{ MPa}
\]

and the corresponding principal stress is:

\[
\sigma_{\text{max}} = \sigma_{\text{ave}} + \sqrt{(\sigma_x - \sigma_{\text{ave}})^2 + (\tau_{xy})^2}
\]

(A-1-5)
Where: \( \frac{\sigma_{\text{ave}}}{\alpha} = \frac{\sigma_x + \sigma_y}{2} = \frac{124 + 0}{2} = 62 \text{ MPa} \)

\[
\Rightarrow \sigma_{\text{max}} = 62 + \sqrt{(62)^2 + (36.1)^2} \\
= 134 \text{ MPa} < 165 \text{ MPa} \quad \text{OK!}
\]
Element B (H38 - 152 x 152 x 13)

(a) FE Analysis

- Loading is assumed to be uniformly distributed over washers.
- 'Interactions' and 'supports' are defined the same way as in Element A

**Results**

Max. principal stress = 152 MPa < 165 MPa

ok!

(b) Approximate hand calculations (as a check)

H38 152 x 152 x 13

\[ P = \frac{800}{4} = 50 \text{ kN} \]

\[ R = 100 \text{ kN} \]

- No torsion is available
- Worst analogy would be as this:

\[ \Delta \]

\[ 100 \text{ kN} \]

\[ l_n = 120 \text{ mm} \]

\[ (A - A - 8)_{t_3} \]
\[ \Rightarrow V_{\text{max}} = \frac{50}{0} \text{ kN} \]
\[ M = \frac{3}{0} \text{ kN} \cdot \text{m} \]
\[ S_{\text{w, c}} = 276 \times 10^3 \text{ mm}^3 \times 40\% = 110.4 \times 10^3 \]
\[ a = \frac{M}{S} = \frac{3 \times 10^6}{110 \times 10^3} = 27.3 \text{ MPa} \]

For simplicity, the effect of horizontal component of the applied load has been converted to the equal vertical shear reactions:

Thus, doubling the available shear effect, could be considered as a conservative way to take the effect of the horizontal component of the applied load into consideration:

\[ C = \frac{2 \times 50 \times 10^3}{2 \times 15.2 \times 707.4 \times 12.7} = 37 \text{ MPa} \]

\[ \text{account for the available slots} \]

\[ \Rightarrow T_{\text{max, principal}} = 53.1 \text{ MPa} < 165 \text{ MPa} \quad \text{OK!} \]

(Note: The results from approximate analysis (A-D-9).)
is much less than that obtained from finite element analysis. This might be due to the assumption made to account for horizontal load component which might be wrong or might be due to the relatively large slots available which cause severe stress concentration.

(A-J-10)
Element C (HSS - 305 x 203 x 13)

(a) FE analysis

Assumptions:
The same as those taken for 'Element A'

Results:

Max. principal stress:

\[ 117 \, \text{MPa} < 165 \, \text{MPa} \quad \text{OK!} \]

(Results are graphically shown in the following pages)

(b) Approximate hand calculations (As a check)

\[ V_{\text{max}} = 100 \, \text{kN} \]
\[ M_{\text{max}} = 60 \, \text{kN}\cdot\text{m} \]

\((A. J_{277})\)
Check for bending:

\[ S_{xy} = 769 \times 10^3 \times 707 \times \frac{1}{2} = 538.3 \times 10^3 \text{ mm} \]

(* To account for the slots available, less reduction factor is used since slots are farther from centre)

\[ \sigma = \frac{M}{S_{xy}} = \frac{60 \times 10^6}{538.3 \times 10^3} = 111.5 \text{ MPa} \]

Check for shear and torsion

\[
\begin{align*}
V &= 100 \text{ kW} \\
T &= 10 \text{ kN.m} \\
\Rightarrow \tau &= \max \left\{ \frac{(V + T/0.305) \times 10^3}{2 \times 203 \times 12.7}, \frac{T/0.203 \times 10^3}{2 \times 305 \times 507 \times 12.7} \right\} = 12.7 \text{ MPa} \\
\end{align*}
\]

(* To account for available slots)

\[ \tau_{\text{max}} = \tau_{\text{ave}} + \sqrt{(\sigma_m - \tau_{\text{ave}})^2 + \tau_{\text{xy}}^2} \]

Where:

\[ \tau_{\text{ave}} = \frac{\tau_m + \tau_y}{2} = \frac{\sigma_n}{2} = \frac{111.5}{2} = 55.8 \text{ MPa} \]

\[ \sigma_n = 111.5 \text{ MPa} \]

\[ \tau_{\text{xy}} = 25.8 \text{ MPa} \]

\[ \Rightarrow \tau_{\text{max}, \text{principal}} = 117.3 \text{ MPa} < 165 \text{ MPa} \]

(A-J-13)
T-section and the required welding for Elements A & C

Assumptions:

* Case of Element A is considered conservatively.

* Rolled edge => \( D_{\text{max}} = 0.75t = 0.75 \times 17.4 = 13.05 \text{ mm} \)

** Take \( D = 12 \text{ mm} \)

\[ a = \frac{12}{12} = 8.5 \text{ mm} \]

* Check enough space for grip:

\[ d - k = 108 - 34 = 74 \text{ mm} < 90 \text{ mm} \]

> ok

* Web crippling check:

\[ B_r = \min \left\{ \frac{\Phi_{br} \omega (N+10)}{E_d} \left( \frac{S16.01}{cl.14.3.2} \right), 1.45 \Phi_{br} \omega \sqrt{E_d} \right\} \]

Where:

- \( N = 100 \text{ mm} \) (The grip length to be conservative)
- \( t = 17.4 \text{ mm} \)
- \( \omega = 10.2 \text{ mm} \)
- \( E_d = 350 \text{ MPa} \)

\((A-J-2015)\)
\[ E = 200 \times 10^3 \text{ MPa} \]
\[ \Phi_{bt} = 0.80 \]
\[ (N + 10t) < \frac{254 \text{ mm}}{455 \text{ width}} \]
\[ \Rightarrow B_r = \text{mm} \quad \left\{ \begin{array}{l}
725.4 \text{ kN} \quad \text{Governs!}
\hline
1009.7 \text{ kN}
\end{array} \right. \]

\[ B_r > R = 200 \text{ kN} \quad \text{OK!} \]

4. Check local yielding in the web for the worst case [§16.01; Cl. 13.10]

\[ B'_r = 1.5 \Phi F_y A \]
\[ B'_r = 1.5 \times 0.9 \times 350 \times 100 \times 10.2 \]
\[ = 482 \text{ kN} > 200 \text{ kN} \quad \text{OK} \]

4. Check the capacity of the proposed welding detail in compression (as the dominant loading mode)

\[ l = (\text{length of the weld}) = (2 \times 250) + [2 \times (206 - 2 \times 15)] \]
\[ + [8 \times (80 - 20)] \]
\[ = 1332 \text{ mm} \]

\[ (A.8-16_{28}) \]
\[ V_r = 0.67 \phi_3 A \omega X_u \rightarrow [ S16.01; \text{Table 3.24} \]

\[ \theta \text{ is taken } 90^\circ \text{ for all welding lines conservatively} \]

- E49XX is assumed to be used.

\[ D = 12 \text{ mm} \rightarrow \frac{V_r}{r} = 1.87 \frac{\text{kN}}{\text{mm}} \text{ (Table 3.24)} \]

\[ \Rightarrow V = 1.87 \times 1300 = 2431 \text{ kN} \gg 200 \text{ kN} \]

\[ \text{[Note: Even for E43XX, } V = 2132 \text{ kN] Q\#k} \]

* Check the capacity of the proposed welding detail in tension (just in case)

From 'Illustrative examples of detail categories' [S16.01; Fig. 2], the current welding detail is a combination of Example 19 (Category C*) and Example 16 (Category E). For this special category C*, the code gives the following equation:

\[ F_{\text{ort}} = F_{\text{ort}}^C \left[ (0.06 + 0.79 \frac{H}{t_p})/(0.64 t_p^{0.6}) \right] \]

\[ = 69 \left[ (0.06 + 0.79 \times \frac{12}{17.4}) / (0.64 \times 17.4^{0.6}) \right] \]

\[ = 40.5 \text{ MPa (Base metal)} \]

\[ (A-A-17)^2 \]
For category E, we have:

\[ F_{srE} = 31 \text{ MPa} \quad \text{(Shear stress on weld throat)} \]

Category E criteria for all welding lines, thus, has been taken conservatively:

\[ T = 1300 \text{ mm} \times \left(\frac{12}{\sqrt{2}}\right) \times 31 \text{ MPa} \times 10^{-3} \]

\[ = 342 \text{ kN} > 200 \text{ kN} \quad \text{OK!} \]

Another possible failure path would be along the line, shown in the following figure, based on the base metal stress:

Thus:

\[ T = 0 \times 0 \times F_{srE} \]

\[ = 2 \times (354 + 206) \times 12.7 \times 40.5 \times 10^{-3} \]

\[ = 473.2 \text{ kN} > 200 \text{ kN} \quad \text{OK} \]
Element G1 (Threaded rods)

*Note: The real $F_y$ for the threaded rods should be higher than 350 MPa, since the $F_{u, min}$, given for them, is 125,000 psi ($\approx 860$ MPa). However, to be conservative, $F_y$ is assumed to be the same, i.e. 350 MPa in the following calculations.

* To design these elements, an analogy to columns has been made:

\[ P = 50 + \frac{10}{0.114} = 138 \text{ kN} \]

\[ V = 50 \times 50\% = 25 \text{ kN} \]

\[ A_{b, eff.} = 0.75 \times A_b = \frac{0.75 \times \pi \times 38^2}{4} = 850 \text{ mm}^2 \]

(*Because of being threaded [Cl. 13.12.3.1](#))

\[ \sigma = \frac{P}{A_{b, eff}} = \frac{138 \times 10^3}{850} = 162 \text{ MPa} < 350 \text{ MPa} \]

\[ \tau = \frac{V}{A_{b, eff}} = \frac{25 \times 10^3}{850} = 29 \text{ MPa} < 165 \text{ MPa} \]

\( (A. A. 19) \)
Notes: 1. There is not a significant possibility for fatigue, since mostly in compression.

2. For the case in tension, the load effect is less than this (at least half), thus still safe!

Check for slenderness effect:

Although the maximum free length of the rod would be $178 \text{ mm} (= 203 - 2 \times 12.7)$, however to be conservative, its whole length is taken into consideration and the $k$ value is assumed to be 1:

$$k_l = 500 \text{ mm}$$

$$r = \sqrt{\frac{I}{A}} = \sqrt{\frac{1}{4} \frac{\pi R_{\text{eff}}^4}{\pi R_{\text{eff}}^2}} = \frac{R_{\text{eff}}}{2}$$

Where:

$$R_{\text{eff}} = \sqrt{\frac{0.75 \pi A_b}{\pi}} = \sqrt{\frac{850}{\pi}} = 16.4 \text{ mm}$$

$$\Rightarrow r = 8.2 \text{ mm}$$

$$\therefore \frac{kl}{r} = \frac{1 \times 500}{8.2} = 61$$

$$\lambda = \frac{kl}{r} \sqrt{\frac{F_y}{\pi^2} E} = 0.812 \quad [C1.13.3.1]$$

$(A-1-820)$
\[
\begin{align*}
n &= 1.34 \\
C_r &= \Phi A_b^{eff} F_d \left( 1 + x^2 \right)^{-\frac{1}{n}} \\
      &= 0.9 \times 850 \times 350 \times \left( 1 + 0.812 \right)^{2.68 - \frac{1}{1.34}} \\
      &= 191 \text{ kN} > 138 \text{ kN} \quad \text{OK}
\end{align*}
\]
Element H (L 4" x 3" x 1/4" or 102 x 76 x 13)

\[ P_x = \frac{H}{4} = \frac{90}{4} = 22.5 \text{ kN} \]

\( ^* P \) applies to one section

\[ M = P \times 0.052 = 1.2 \text{ kNm} \]

\[ M_{60\text{mm}} = \frac{M}{0.060} = 20 \text{ kN} \]

\[ R = \sqrt{11.25^2 + 20^2} = 23 \text{ kN} \]

\[ V_r^* \text{ (in bolt)} = 0.7^* \times 0.6 \times \Phi_b \times \text{max} \times F_u \times A_b \quad [\text{cl. 13.12.1}] \]

\( ^* : \text{For the worst case} \)

where:

\[ m = 1 \]

\[ n = 1 \]

\[ F_u = 825 \text{ MPa} \]

\[ A_b = 314 \text{ mm}^2 \quad (M20 \text{ bolt}) \]

\[ \Phi_b = 0.8 \]

\[ V_r^* = 87 \text{ kN} > 23 \text{ kN} \quad \text{OK} \]

\[ V_r^* \text{ (in plate)} = \min \left\{ \frac{(180 - 2 \times 24) \times 12.7 \times 0.6 \times F_u}{0.9 \times 450}, \frac{130 \times 12.7 \times 0.6 \times \Phi_b \times F_j}{0.9 \times 350} \right\} \]

\( (A - J_{20722}) \)
\[ \text{min} \left( \frac{253}{312} \right) \]

\[ V_{C_{\text{plate}}} = 253 \text{ kN} > 23 \text{ kN} \text{ ok} \]

\[ B_{r} = 3 \Phi_{br} \text{td} nF_{u} \quad [\text{Cl. 13.10.c}] \]

\[ = 3 \times 0.67 \times 12.7 \times 20 \times 2 \times 450 \]

\[ = 451 \text{ kN} > 2 \times 23 = 46 \text{ kN} \text{ ok} \]

Check the behaviour of the pre-tensioned bolt in SLS \[ [\text{Cl. 13.12.2.2}] \]

\[ V_{s} = 0.53 c_{1} k_{s} m_{n} N_{b} F_{u} \]

where

\[ c_{1} = 0.82 \quad \rightarrow \text{Table 3 (316.01)} \]

\[ k_{s} = 0.33 \]

\[ = 0.53 \times 0.82 \times 0.33 \times 1 \times 1 \times 314 \]

\[ = 37 \text{ kN} > 23 \text{ kN} \text{ ok} \]

\[ \therefore \text{ The designed set-up is safe!} \]