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Guidelines for Shear Strengthening of Beams Using Carbon Fibre-Reinforced Polymer (FRP) Plates

Ma'en S. Abdel-Jaber[1], Anis S. Shatanawi[2] and Mu'tasim S. Abdel-Jaber [2]

[1] Assistant Professor, Applied Science University.
[2] Assistant Professors, The University of Jordan. ashatnawi@ju.edu.jo. (Corresponding Author).

ABSTRACT

The fundamental aim of this work is to give clear guidelines for the process of strengthening reinforced concrete beams using FRP materials. Types and methods of FRP construction are described in general. FRP properties and their effect on strengthening are illustrated.

Experimental results obtained from an earlier study are utilized in this research to present a reasonable model for strengthening. The experiments investigated the shear behaviour of reinforced concrete beams strengthened by the attachment of different configurations and quantities of CFRP using epoxy adhesives. Two types of CFRP materials were used. These are pultruded and prepreg materials. A general comparison between results is carried out showing the best configuration for strengthening.

In this paper, it is clearly stated that moderate surface treatment for concrete before FRP bonding is sufficient to allow FRP to do its job in a proper way. In general, it is adequate to remove all laitance and loose material by hand or machine abrading, followed by degreasing with a detergent and rinsing clean.

Keywords: Shear Strengthening, Beams, Polymer Plates, Fibre-Reinforced Polymer (FRP).

1. INTRODUCTION

External plate bonding is a method of strengthening which involves adhering additional reinforcement to the external faces of a structural member. The success of this technique relies heavily on the physical properties of the material used and on the quality of the adhesive, generally an epoxy resin, which is used to transfer the stresses between the flexural element and the attached reinforcement. The first reported case strengthened by this technique was in 1964. Epoxy-bonded mild steel plates were applied to load bearing beams in the basement of an apartment building, in Durban in South Africa (McKenna and Erki, 1993).

In the 1980s, Swiss researchers at the Swiss Federal Laboratories for Materials Testing and Research called EMPA pioneered studies on the uses of Fibre Reinforced Plastic Materials (FRP) as a replacement for steel in strengthening applications. These materials -unlike steel- do not suffer from corrosion and their other mechanical and physical properties can be better than steel.

2. FRP MATERIALS

Man-made fibres were first produced at the end of the nineteenth century. Synthetic fibres have an even shorter history of less than fifty years. Chemists started to develop synthetic resins, firstly phenolics and then polyesters and epoxies. The first uses of these materials as matrices probably occurred towards the end of World War II. Within a few years of the introduction of polyester resins, they were being used with glass

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reinforcement. Many artefacts such as boats began to appear during the 1950's. The development of synthetic polymers has led to the development of high performance polymer composites, high modulus, high strength continuous filaments, like boron and later carbon, and has profoundly impacted on today's aerospace airframe design and manufacturing.

Progress in recent years has clearly indicated that the category of composite materials based on fibre reinforcement bonded with synthetic resin has considerable potential for use in engineering components and structures.

3. FIBRE TYPES

Details of the mechanical properties of a range of reinforcing fibres are listed in Table (1). Different types of fibres can be used in manufacturing the FRP materials such as the following (Kendall, 1999):

E-Glass

The most common reinforcing fibre is E-Glass, which derives its name from its electrical resistance. E-glass is available in a variety of forms such as continuous rovings, woven rovings, stitched fabrics, unidirectional tapes and chopped fibre mats or Chopped Strand Mat (CSM) as it is commonly known. The fibre is very economical and of moderate strength but low modulus (stiffness).

C, R and S Glass

C glass is a chemical resistant grade mainly used in the production of surface tissues to protect the surface of a laminate. R glass and S glass are high strength grades.

Aramid

Aramid, or Polyaramid fibres such as Kevlar 49 are man-made organic fibres offering very high tensile strengths and low density. Aramid fabrics are very soft and easy to handle.

Carbon

Carbon fibre is the most expensive of the more common reinforcements, but due to its very high strength and stiffness it is the most commonly used fibre.

Polyethylene

Polyethylene (PE) is generally regarded as a cheap, low strength utility plastic.

4. PULTRUDED FRP

Pultrusion is a technique for the continuous manufacture of fibre reinforced composite profiles. By incorporating glass, carbon, aramid or other high performance fibres into a range of high performance resins, physical properties can be achieved to meet the needs of engineers in a wide variety of applications.

The pultrusion process generally consists of pulling continuous rovings and/or continuous reinforcement fibres through a resin bath or impregnator into pre-forming fixtures where the section is shaped and excess resin and/or air is removed, then into heated dies where the section is continuously cured producing a tough material as shown in Figure (1). The process can be simply visualized as extrusion with pulling of raw materials rather than pushing them through the die. The production line is capable of forming round tubes, rectangular tubes, plates, rods or any other linear sections.

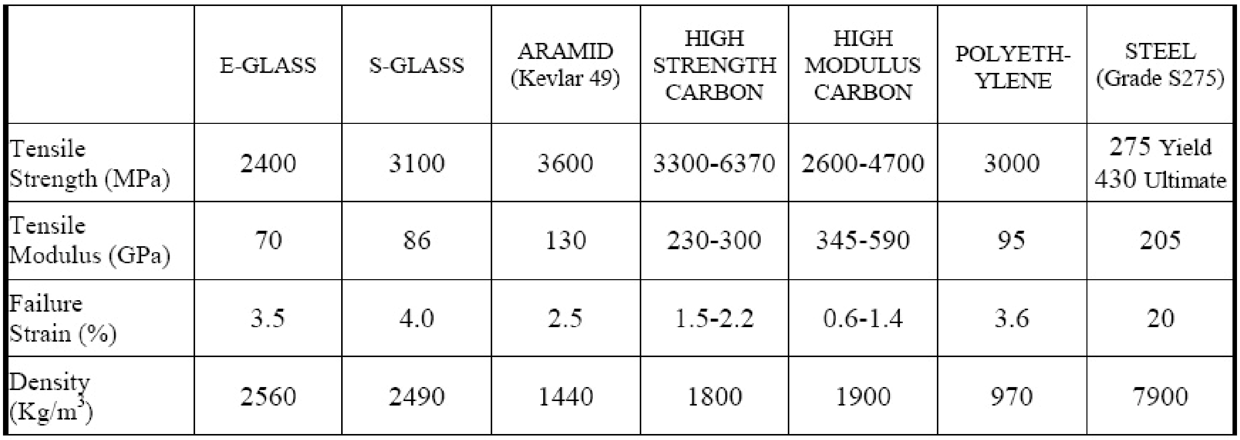
5. PREPREG FRP

Pre-impregnated materials (prepregs) provide the most precise way of combining reinforcements with the resin matrix. Prepregs are semi-finished products with unidirectional single layers of fibre (with all the fibres in this layer aligned parallel to each other) or woven fibres pre-impregnated with resin (several directions of reinforcement).

Prepreg technology allows the toughest and strongest matrix systems to be combined with all fibre types currently used in advanced composite components. Furthermore, prepregs reduce the possibility of processing errors during fabrication.

The prepreg sheets are stacked on the mould surfaces in predetermined orientations, covered with a flexible bag and consolidated using a vacuum or pressure bag in an autoclave or oven at the required curing temperature. Prepreg sheets are very flexible and can be formed into many different shapes as shown in Figure (2).

Table 1: Typical Fibre Properties.



	E-GLASS	S-GLASS	ARAMID (Kevlar 49)	HIGH STRENGTH CARBON	HIGH MODULUS CARBON	POLYETH-YLENE	STEEL (Grade S275)
Tensile Strength (MPa)	2400	3100	3600	3300-6370	2600-4700	3000	275 Yield 430 Ultimate
Tensile Modulus (GPa)	70	86	130	230-300	345-590	95	205
Failure Strain (%)	3.5	4.0	2.5	1.5-2.2	0.6-1.4	3.6	20
Density (Kg/m^3)	2560	2490	1440	1800	1900	970	7900

Table 2: Direction of CFRP Fibres in Beam Specimens.

Specimen	Fibre Direction
B11	Horizontal
B12	Vertical
B13	45°
B14	Horizontal (precracked)

Table 3: Increases in Ultimate Load for Each Beam Type Tested.

Beam Reference	Increase in Ultimate Load (%)	Beam Reference	Increase in Ultimate Load (%)
B1	0	B9	+29
B2	+56	B10	+44
B3	+40	B11	+122
B4	0	B12	+117
B5	-17	B13	+109
B6	+23	B14	+89
B7	+22	B15	+93
B8	+19	B16	+78

6. SHEAR FAILURE IN BEAMS

A reinforced concrete element is normally designed to develop its full flexural strength to ensure a ductile flexural failure mode under excessive loading. Shear failure in reinforced concrete beams normally takes a form similar to that shown in Figure (3). Shear failure is a brittle type of failure, which is more dangerous and less predictable. All beams of structural significance contain links to increase the shear resistance of the section. One possible method of increasing the shear strength is by bonding FRP to the vertical surfaces of the beam.

7. TEST PROGRAMME

A series of 38 beams were produced, all of which were designed to fail in shear. These were strengthened using CFRP methods in various configurations in combination with other factors. The variables were:

- Percentage main (bottom) reinforcement.
- Link spacing in shear span.
- Configuration of CFRP strengthening.

Only test series B is described here, the details of which are shown in Table (2) and Figures (4-5). Shear links were omitted in these beams from the shear spans and 2% of main reinforcement was provided in the bottom.

The materials used were as follows:

- Concrete with an average 150mm cube strength f_{cu} = 61.8 MPa.
- Hot-rolled high yield deformed main reinforcement with a strength of f_y = 420 MPa.
- Sika CarboDur S1012 pultruded unidirectional CFRP material of 100 mm width and 1.2 mm thickness, fibre volume = 68% in an epoxy matrix, ultimate tensile strength (UTS) = 3100 N/mm^2 and modulus of elasticity = 155 kN/mm^2 bonded with Sikadur 30 (beams B2-B14).
- SikaWrap Hex 103C CFRP fabric, 0.27 mm thick, UTS = 3500 MPa bonded with Sikadur 330 (beams B15-B16).

Beams B2 and B5 to B10 were strengthened by bonding CFRP strips in different configurations to both vertical faces in the shear spans. Beams B3 and B4 had 100mm-wide CFRP strips bonded to the soffit. Beams B11 to B14 were strengthened by bonding plates to both vertical faces over the entire shear span with different fibre orientation (see Table 2). Beams B15 and B16 were respectively strengthened with one and two layers of Sika Wrap attached to the beam sides and soffit over the shear span. Four-point incremental load tests were carried out to failure and measurements were made of deflections, crack widths, ultimate loads and strains in concrete, CFRP and reinforcement.

8. CONCRETE SURFACE PREPARATION AND BONDING OF CFRP

Tests were also undertaken to establish the effect of concrete surface treatments on the bond between the adhesive and the concrete. A series of pull-off tests were undertaken at 40 days on concrete surfaces, half of which had been air-cured, the remainder being water-cured. In addition to control mixes without surface treatments, the following were applied:

- Grit-blasting and blowing clean with compressed air.
- Wire-brushing followed by hand-abrading with a carborundum stone, then cleaning with compressed air, followed by washing with ordinary diluted detergent and rinsing.

Regardless of the surface treatment, failure always occurred in the concrete, thus showing that the bond between the adhesive and the concrete was adequate and unaffected by the surface treatment or curing conditions.

All beam surfaces were treated using the second method and the CFRP was wiped with a proprietary cleaner. The adhesive was spread on the concrete surface with a thickness of approximately 2 mm and on the CFRP plates at approximately 1 mm thickness. The plates were applied using the moderate pressure of a roller to remove any air bubbles and ensure a good bond. For the SikaWrap, adhesive was applied to the beam, the Wrap laid and a further coat of adhesive then rolled on.

9. RESULTS

The control beam B1, beams B3-B4 with CFRP on the soffits, beam B5 and those strengthened with SikaWrap all failed by the development of shear cracks in the concrete (see Figure 5). The failure of the beams with plates over the entire shear span (B11-B14) was explosive with little warning and probably compressive in nature. All remaining specimens, reinforced with CFRP strips, failed due to shear and delamination of the strips (see Figure 5). In all cases, failure occurred in the concrete rather than the adhesive, thus emphasizing how important it is to adequately anchor the strips on each side of the shear crack.

All strengthened beams showed an increase in shear strength, except beam B4 where there was no change and beam B5, which decreased by 17% (see Table 3). In the latter case, this may have been caused by stress and shear crack redistribution. The increase in shear strength of the remaining arrangements ranged between 19% in beam (B8) and above 109% for the beams with plates over the entire shear span (B11-B13). Beam B14, which had been precracked showed an increase in shear strength of 89%. Beam B2, which was strengthened by two horizontal strips distributed over two-thirds of the beam depth, showed an increase of 56% and this arrangement may represent the most efficient use of the CFRP considering its high material cost. The beams strengthened with SikaWrap (B 15 and B 16) exhibited an increase in strength of about 80-90%, but the addition of a further layer seemed to have no effect on the strength.

10. CONCLUSIONS

Advanced composites are increasingly being used in the construction industry due to their inherent advantages over traditional materials including their lightweight, high strength, ease of application and low maintenance costs. The conclusions below embrace practical recommendations for strengthening reinforced concrete beams in shear using CFRP plates and woven carbon fibre "wrap fibre":

- The Sikadur 30 adhesive bonded adequately with the concrete regardless of the curing method and surface treatment. In general, it is adequate to remove all laitance and loose material by hand or machine abrading, followed by degreasing with a detergent and rinsing clean.
- The application of CFRP strips to the shear spans of the beams increased the strength between 19% (B8) and 56% (B2). The increase in strength was governed by the anchorage of the strips on each side of the projected shear crack. The application of two horizontal CFRP strips over the shear span and tension zone (such as beam B2) appears to be an efficient method of shear strengthening.
- The greatest increase in shear strength was achieved by bonding plates over the entire depth and shear span (B11-B14). However, subsequent failure was sudden and with very little warning.
- The application of SikaWrap 103C to the soffit and sides of the shear span increased the shear strength by 80-90%.

Figure (1): Pultruded Carbon Fibres.

Figure (2): Prepreg Carbon Fibre.

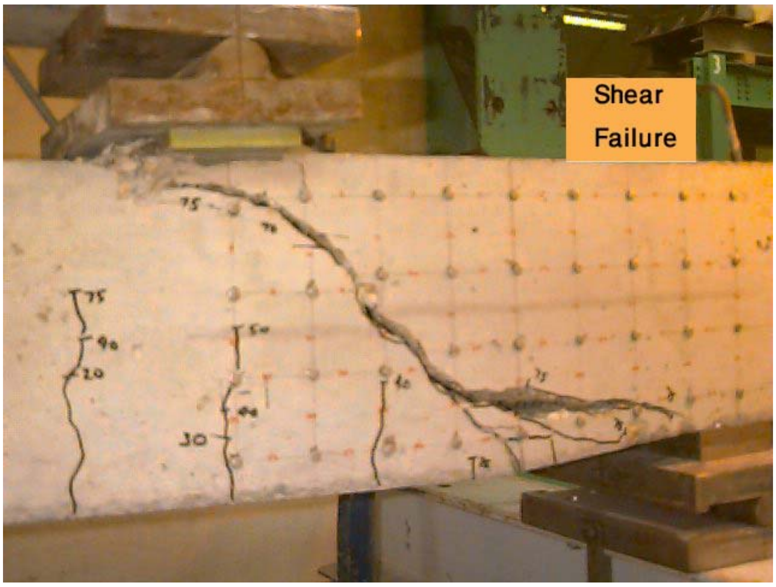


Figure (3): Typical Shear Failure Crack.

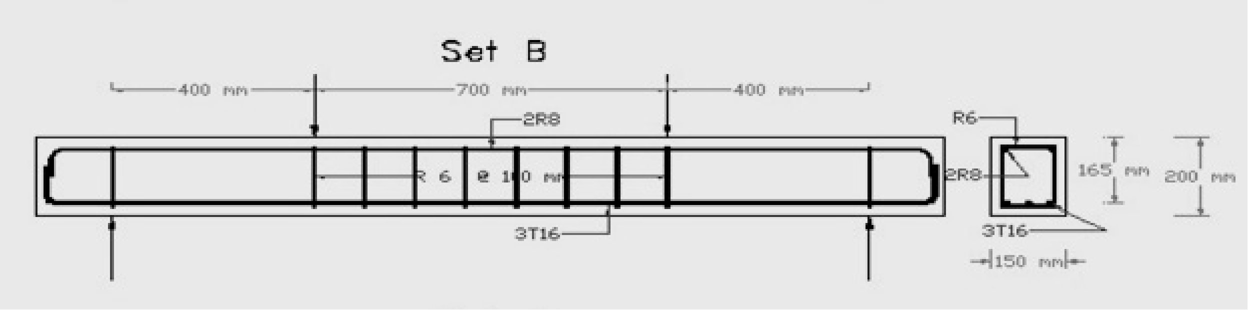


Figure (4): Control Beam for Set B.

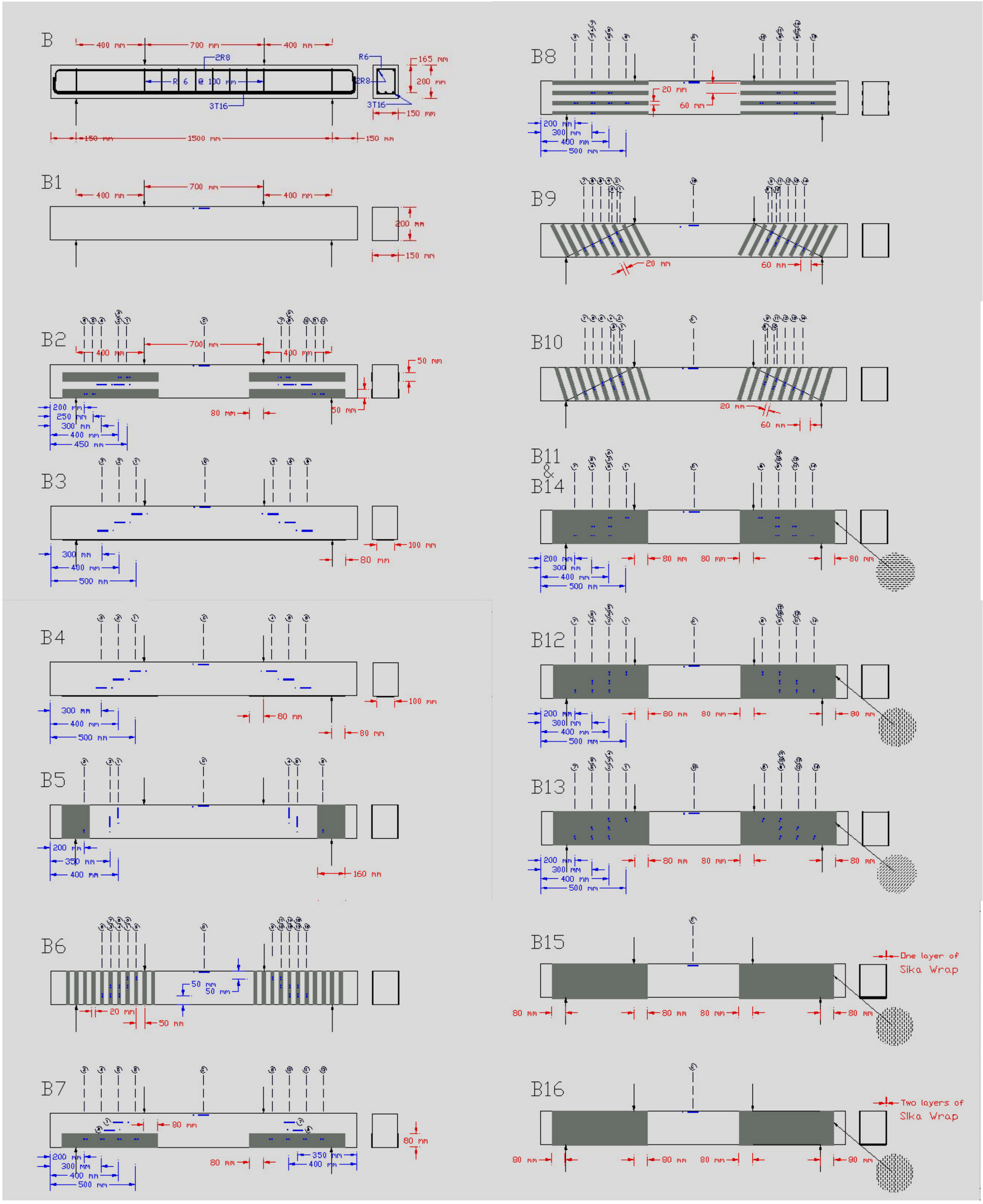
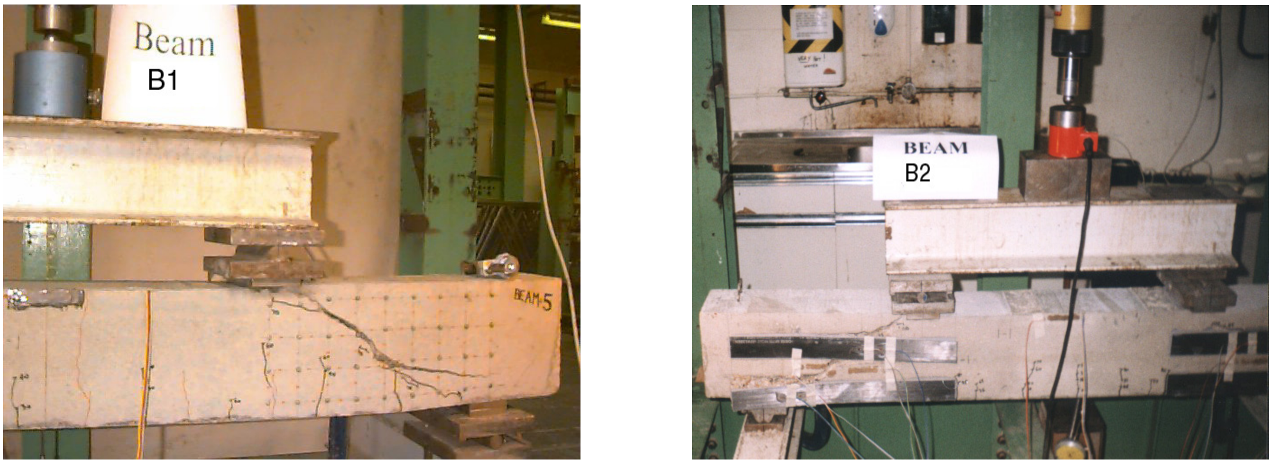


Figure (5): Configurations of CFRP Strip for Each Test Beam.



a) Beam B1 d) Beam B2

b) Beam B6 e) Beam B7

c) Beam B8 f) Beam B16

Figure (6): Typical Failure Modes for Some Beams.

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