An Experimental Study on Flexural Strengthening of Structural Steel Angle Sections Using Carbon Fiber-Reinforced Polymer (CFRP) Composites

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Abstract

Globally, there is need for strengthening of steel structures due to increased load carrying requirements, changes in earthquake / wind codes and rehabilitation due to corrosion degradation. Advanced composites have become one of the most popular techniques of repairing and/or strengthening civil infrastructure in the past couple of decades. The use of FRP material for the repair and rehabilitation of steel members has numerous benefits over the traditional methods of bolting or welding of steel plates. Carbon FRPs (CFRPs) have been preferred over other FRP material for strengthening of steel structures due to CFRPs possess higher stiffness. The emergence of high modulus CFRP, with an elastic modulus higher than that of steel, enables researchers to achieve substantial load transfer in steel beams before the steel yields.

In the present work, experimental investigation is carried out to analyze the behavior of steel angle sections wrapped with carbon fiber reinforced polymer (CFRP) to increase flexural strength and stiffness of parent structural member steel angle section due to CFRP wrapping. A total of 4 tensile coupon tests are conducted to determine the engineering properties of structural steel used. A novel flexural strengthening technique using bonded CFRP wrapping to enhance the strength and stiffness of existing steel angle sections has been developed. This is carried out by varying the CFRP wrap configurations and keeping adhesive properties constant. The experimental program consists of two sets each with 15 specimens to test a total of 30 specimens. Each set has five subsets as four different strengthening configurations and a set representing reference control specimens. The parameters studied include the slenderness ratio (b/t) of steel angles, the thickness and orientation of the CFRP wrap, comparative study on behavior of strengthened specimens, investigation on stiffness enhancement and strain variation across the section in relation with load.

This research investigated experimentally the behavior transformation of open sections into closed section, stiffening enhancement in elastic region and strength enhancement in both elastic and post yield regions of high strength CFRP strengthened structural steel angles tested under four point bending system in comparison with bare steel angles. Proposed external wrapping (bonded) CFRP reinforcement has been clearly established as a promising alternative to existing strengthening technique for steel structures. This proves that CFRP strengthening can be employed with proposed strengthening configuration to achieve desired degree of effectiveness and efficiency. The new strengthening approach has resulted in novel wrapping technology which has been first time applied to structural steel angle section (open section).

KEYWORDS: Carbon Fiber Reinforced Polymers (CFRP), Adhesive, Structural steel angle section, Wrapping, Strengthening.

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Chapter 1

Introduction

1.1 Main Feature

Novel approaches are required for strengthening and rehabilitation of significant numbers of steel structures in India and in general all over the world those which are structurally deficient and require maintenance. These deficiencies may be caused due to increased load carrying requirements, changes in earthquake and wind design provisions or by deterioration of the structure due to corrosion. A considerable amount of research work has been carried out using carbon fiber reinforced polymer (CFRP) as strengthening material for concrete. The technology is well established that design codes such as ACI440.2R-08 are available for strengthening of concrete structures.

With the introduction of high-modulus CFRP materials, the possibility for providing a solution to the ongoing problem of infrastructure deterioration may be extended to steel structures as well. While the transfer of the technology from one material to another may initially seem straightforward, it is complicated by several potential problems. More strengthening material or higher grade material is needed to achieve a significant strength increase, as steel has higher load carrying capacity than concrete, especially in tension. But as more strengthening material is added the bond stresses become more critical as well as the fact that the material may be used less effectively due to the shear lag effect. These problems will be offset if a robust and low-cost means of rehabilitating and strengthening steel structures may be achieved. Not only the construction costs, but indirect costs such as the disruption to the public and the environmental costs of disposal and replacement of older structures may also be reduced. Since many of the structures built in the post-independence era are already past their design life, the inventory of deteriorated steel structures in need of rehabilitation can only be expected to increase.

1.2 Research Objective

While FRP materials have been successfully used for flexural strengthening, shear strengthening and ductility enhancement of concrete bridge structures, there are a large number of steel structures in need of strengthening. Specifically, three end users have been identified for strengthening and rehabilitation systems. They are the power industry, telecommunications transmission industry and departments of transportation. Increasing number of cellular phone users and their requirement for improved service has required telecom companies to increase the number of transmitting systems using steel towers. Same is the case with electricity transmission towers as number of end user are increasing and also to support the government policy to provide electricity to every Indian citizen regardless of his or her location even in the remotest place to ensure quality power supply. This results in increased system installation load. However, this trend has been exasperated due to land scarcity, environmental degradation and obstruction to scenic views. Addition of new power cable systems on existing transmission towers increases the load acting on towers, requiring a need for strengthening. Existing techniques for strengthening tower structures with an additional lattice structure are expensive in addition to negatively affecting the visual appearance of the structure. Transportation departments also demand strengthening and rehabilitation systems for steel bridges.

The strengthening system should be both cost effective and should not cause major interruption to traffic. As such, the purpose of this research was to develop a system using CFRP materials to strengthen steel angle members of steel tower and steel bridges. Unlike concrete members (mostly closed section), where the behavior is almost same between cross sections. The mode of failure for steel sections is a function of the cross section. Therefore a technique that is applicable for one particular section may not necessarily be suitable for an open section. The overall goal of this research work is to investigate a new promising approach for rapid and efficient strengthening of steel angle sections.

1.3 Scope and Contents

Chapter – 1, gives the introduction to the present situation of strengthening of steel structures and research objective.

In Chapter – 2, a review of previous work in the area of strengthening of metallic structures with FRP material was conducted. This includes early research on structures strengthened with standard modulus CFRP materials. This includes an examination of the previous CFRP bonding techniques and testing results. Also included is the investigation of bond performance as well as geometrical consideration of the joint, and its long-term durability.

Chapter – 3, describes the details of the organization of experimental test set up including the geometric and material properties of the test specimens, fabrication of test specimens, methodology for application of CFRP to structural steel angle sections, the test matrix and the instrumentation planned and executed.

Chapter – 4, presents the experimental results, failure modes observed, comparison among distinct wrap configurations, inferences drawn from results, conclusion and summary of experimental results.

Chapter – 5, present’s details about the future work needs to be carried out in the same research area.

Chapter 2

Background

2.1 Overview

Increased loads, changes in earthquake / wind codes and corrosion degradation in conjunction with many steel structures predominantly tower structures approaching the end of their design life, are the causes for many steel structures posted to limited load carrying capacity. For steel structures, a deficiency due to corrosion that results in cross-section losses is serious problem. Corrosion damage can cause progressive weakening of structural elements, but it may also be localized in the form of pits and holes causing stress concentrations. Corrosion may also reduce the flexural strength in a region subjected to a high bending moment, because eccentricities in loading of structural elements, cause web buckling or crippling and result in reduction of the fatigue resistance of the member.

Apart from the need for structural rehabilitation, strengthening may also be required due to changes in earthquake / wind codes. Because according to changed codal provisions it needs to prove the safety of the existing structure and if structure under consideration is not safe to serve the design loads there are only two alternatives. First, declare the structure unfit for use and construct a new one and second, go for structural rehabilitation. The second alternative sounds well as it would be increasing the strength of parent structure in all structural strength respects to make it structurally fit to serve the design loads over the former alternative where we have to destruct the existing structure and then reconstruct the new one and again get into the complicated activities of land acquisitions and reconstruction.

The literature review is presented in six sections. The first section provides an overview of the development of strengthening metallic structures using FRP materials, initially with their application in the aircraft industry to the most recent demonstration projects for strengthening bridges with CFRP materials. The behavior of bonded joints, especially metal to composite joints, is then examined. This also includes various techniques used by various researchers for application of CFRP to metals. This is followed by an examination of the durability of bonded joints as well as both the effect of galvanic corrosion and proposed prevention methods. Lastly, experimental investigations of flexural strengthening and flexural rehabilitation using CFRP materials are reviewed. They are summarized as below:

2.1.1 Issues associated with strengthening of steel structures:

Strengthening of steel structures may be required due to the need to increase the load carrying capacity and / or due to damage that has occurred over time that resulted in a lower structural capacity than the designer intended. Typically, these problems are associated either with cross-section losses resulting from prolonged corrosion or fatigue damage that leads to cracking in the vicinity of fatigue sensitive details. Rehabilitation is typically more economical than replacement of the structure, but conventional methods of repair are often less effective and could increase the maintenance costs. Welding used to repair steel structures by adding new material to the reduced area will typically lead to poor strength performance, in addition to the fact that field-welding is likely to be poor. Furthermore, welding can also cause metallurgical changes to the parent material, resulting in premature failure.

To reduce the induced stresses, or to repair corrosion damage of flexural steel members, splices may be bolted over damaged areas, or steel cover plates may be welded along the tension flange of the beam. An alternate rehabilitation method is the application of external post-tensioning. Both of these methods result in the potential for further corrosion damage and the addition of significant dead weight. Furthermore, welding of additional steel plates induces significant residual stresses which could cause poor fatigue performance. If bolting is used instead of welding, the drilling of holes results in loss of cross-section as well as the introduction of local stress raisers, that requires additional strengthening material to be used. Strengthening by bonding FRP materials has been shown to be more suitable for strengthening steel structures than techniques discussed previously. Hollaway and Cadei (2004) presented the first state-of-the-art review in the literature on the use of the FRP material to strengthen steel structures. The authors addressed several issues including, in-service problems associated with advanced polymer composite and metallic adherents, bonding issues in terms of surface preparation and durability, durability of FRP composites in the civil environment, prestressing FRP plates before bonding to metallic beams and field applications.

2.1.2 CFRP Materials for Strengthening Steel Structures;

There are many advantages in favor of the use of CFRP materials for repair and rehabilitation of steel structures. Cost savings may be realized through labor savings and reduced requirements for staging and lifting material. The dead weight added to a structure is minimal due to the high strength to weight ratio of CFRP materials and there is typically little visual impact on the structure, so that good aesthetics can be maintained. Due to the ease of application, disruption of service during construction may be reduced or eliminated. Some FRP application processes allow the FRP to be formed into complex shapes, exactly matching the surface configuration of the existing structure. Application of bonded FRP material results in reduced stress-concentrations as compared to mechanical fastening and does not generate thermal induced residual stresses and heat-affected areas in the metal as welding (Grabovac, 1991).

Overall project costs are typically reduced, when overall costs for a strengthening project are determined, despite the high material costs associated with FRP materials. As the extensive use and demand of CFRP materials will go up the overall cost is going to be reduced. The advantages of the use of carbon fiber to repair metallic structures have been shown in the strengthening of tunnel supports for the London underground railway system (Moy et al, 2001). In this project, the difficult access and the impossibility of a lengthy service shut down led to short-term cost competitive use for CFRP materials. Long-term cost benefits were even more favorable due to the expected durability of the CFRP materials used. Gillespie et al (1996) conducted a cost analysis comparing the cost of rehabilitation with the cost of replacement of a bridge with corroded steel girders. The actual costs were determined from the awarded repair bid for a bridge that had suffered severe corrosion loss. The costs of the rehabilitation were scaled from the costs incurred from the rehabilitation of a girder for testing. The total cost of rehabilitation was 28 percent of the cost of replacement, with most of the cost savings associated with the fact that there is no need to replace the concrete deck in the case of rehabilitation. Thus, although material costs of the CFRP material may be significant, these material costs do not significantly affect the cost benefit since the material costs are often a small portion of the overall project costs.

To reduce the amount of CFRP needed to achieve a given stiffness enhancement, or to more efficiently use standard modulus CFRP materials, prestressed CFRP strips may be used. These strips are stressed before bonding the strip to the steel. With epoxy applied to the prestressed strip, the stress is maintained in the strip until the epoxy is fully cured. Once the epoxy is cured, the stress may be released. While, bonding of unstressed CFRP strips reduces the extra stresses due to live loads placed on a structure, bonding of prestressed strips also relieves existing dead-load stresses.

Bakis et al (2002) conducted a concise state of the art survey of fiber-reinforced polymer also known as fiber-reinforced plastic composites for construction applications in civil engineering are presented. The paper is organized into separate sections on structural shapes, bridge decks, internal reinforcements, externally bonded reinforcements, and standards and codes. Each section includes a historical review, the current state of the art, and future challenges. The most significant mechanical differences between FRP materials and conventional metallic materials are higher strength, lower stiffness, and linear-elastic behavior to failure of the former. Other differences such as the thermal expansion coefficient, moisture absorption, and heat and fire resistance need to be considered as well. The education and training of engineers, construction workers, inspectors, and owners of structures on the various relevant aspects of FRP technology and practice will be crucial in the successful application of FRP materials in construction.

In 1991, the ACI established Committee 440, ‘‘FRP Reinforcement.’’ The committee published a state of the art report on FRP reinforcement for concrete structures in 1996 ACI Committee 440 1996. Committee 440 recently produced two documents approved by the Technical Activities Committee for publication in the year 2001. The documents are 1. ‘‘Guide for the design and construction of concrete reinforced with FRP bars'' ACI Committee 440 2001; and 2. ''Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures.''

From a structural mechanics point of view, an important concern regarding the effectiveness and safety of use of fiber reinforced plastic (FRP) is the potential of brittle debonding failures. Such failures, unless adequately considered in the design process, may significantly decrease the effectiveness of the strengthening or repair application. In recent years, there has been a concentration of research efforts on characterization and modeling of debonding failures. Authors have provided a review of the progress achieved in this area regarding applications to both reinforced concrete and steel members (Buyukozturk, 2004). While separate codal provisions, such as ACI committee 440 has been established for concrete strengthening, no such codal provisions or guidelines exist for strengthening of steel structures with CFRP. No codal procedure is available to test or for addition of amount of CFRP to steel structures. Therefore this literature review was essential for identifying gap in the existing literature and an attempt has been made to fill this gap through this research.

2.1.3 Flexural Strengthening of Steel Members with FRP

The first study to investigate potential applications of CFRP to steel members was conducted at the University of South Florida, where CFRP plates were used to strengthen steel-concrete composite girders that are commonly used in bridge applications (Sen and Liby, 1994). A total of six 6.1 m long beams comprised of steel members (wide flange beam sections) attached to 710 mm wide by 115 mm thick concrete slabs were tested. The specimens were first loaded past yield of the tension flange to introduce damage and then repaired with CFRP laminates. The CFRP laminates used in the study were 3.6 m long, 150 mm wide, and had two different thicknesses of 2 mm and 5 mm. It was reported that the CFRP laminates could considerably improve the ultimate flexural capacity of composite beams. Estimated increases in their ultimate strengths ranged from 11 to 50%, depending on the yield strength of the specimen and the mode of failure.

One significant cause of deterioration of steel bridge structures is the corrosion due to extensive use of de-icing salts in winter weather. The investigation done by Al-Saidy et al (2009) focused on the behaviour of steel composite beams damaged intentionally at their tension flange to simulate corrosion and then repaired with carbon fiber-reinforced polymer CFRP plates attached to their tension side. Damage to the beams was induced by removing part of the bottom flange, which was varied between no damage and loss of 75% of the bottom flange. All beams were tested to failure to observe their behaviour in the elastic, inelastic, and ultimate states. To help implement this strengthening technique, a nonlinear analytical procedure was also developed to predict the behaviour of the section/member in the elastic, inelastic, and ultimate states. The test results showed a significant increase in the strength and stiffness of the repaired beams. Through the use of CFRP plates, all damaged beams were fully restored to their original undamaged state strength.

Tavakkolizadeh and Saadatmanesh (2003) investigated the behaviour of steel-concrete composite girders strengthened with CFRP sheets under static loading. Three large-scale composite girders comprised of 4.9 m long W14x30 A36 steel beams and 75 mm thick by 1 m wide concrete slabs were prepared and tested. The thickness of the CFRP sheet was constant and a different number of layers of 1, 3, and 5 were used in the specimens. The test results showed that, ultimate load-carrying capacities of the girders significantly increased by 44, 51, and 76% for one-, three-, and five-layer retrofitting systems. In addition, the yield load of the girders increased as a result of retrofitting. It is reported that as the number of CFRP layers increased, the efficiency for utilizing the CFRP sheet decreased. Stress in the CFRP laminate for the one-layer system was 75% of its ultimate strength while in the five-layer system, it dropped to 42%. This indicates that a balanced design should be considered to effectively utilize the strength of CFRP laminates.

Colombi and Poggi (2003) discussed the results of an experimental and numerical program to characterize the static behavior of steel beams strengthened with pultruded CFRP strips. H shaped steel beams with different CFRP reinforcement geometries bonded to the tension flanges using different epoxy adhesives were tested under three points bending configuration. Force transfer mechanisms, strength and stiffness of the beams were the main interest of the study.

Results were validated with different analytical and numerical models and with a finite element model which was developed by the authors.

El-Damatty et al (2003) reported an analytical study to investigate the use of Glass Fiber Reinforced Plastic (GFRP) sheets to enhance the flexural capacity of bridge composite steel beams. A detailed finite element model was developed to model the bridge before and after attaching GFRP sheets to the bottom flange of its steel girders. A 25% increase in the truck weight carrying capacity of the girders was reported using the retrofitting scheme.

Lenwari et al (2005) reported on the flexural behavior of steel beams that were strengthened with partial-length, adhesive-bonded CFRP plates. A total of seven steel beams were strengthened with three different CFRP lengths, attached to the bottom flange of the beam and tested under four-point loading. Two different failure modes were observed as plate debonding in beams with short plates; and plate rupture at midspan in beams with long plates. The authors concluded that the attached CFRP plates significantly increased the strength of the strengthened steel beams and extended the elastic range of the beams. An analytical method was also proposed to evaluate the flexural behavior of the strengthened beams.

Haedir et al (2006) also conducted tests on four CHS beams strengthened by CFRP sheets. The main parameters investigated in this study were the number of fiber layers, their orientation and application sequence. It was concluded that longitudinal fiber layers controlled the increase in the moment capacity, whereas transverse fiber layers played a more important role in restraining or delaying the local buckling of the member. It was also reported that specimens with transverse layers applied first to the specimens had their peak moment occurring later compared to the specimens who had longitudinal layers as their first layer.

Patnaik et al (2008) obtained the results by closely studying the behavior of steel beams strengthened with carbon FRP material. They made an attempt to succinctly summarize the findings for two different types of strengthening of the steel beams using carbon FRP laminates. The first type of beams focused on enhancing the strength of steel in flexure while the second focused on increasing the shear strength of the beams. Three beams were designed so as to cause them to fail in flexure. Of the beams studied, two were strengthened using carbon FRP strips attached to the tension flange. One of the beams was tested to facilitate comparison of their behavior to the two beams which are strengthened in flexure. Three other beams were designed such that they failed predominantly in shear. Of these three, two were strengthened with carbon FRP strips attached to the webs while the third beam was used as a control beam for the purpose of drawing comparisons. Preliminary results revealed a noticeable increase in the strength for both the flexure strengthened beams and the beams strengthened in shear. The observed increase in shear strength of the beams was 26% while the increase in strength for the beams tested in flexure was 15%. This study convincingly shows that it is possible to strengthen steel beams using carbon FRP laminates in both flexure and in shear.

2.1.4 Potential modes of failure for a metallic flexural member strengthened using FRP:

J G Teng et al (2012) in his study discussed about the possible failure modes for structural steel (I-beam) flexural member strengthened using FRP. Following figure explains it.

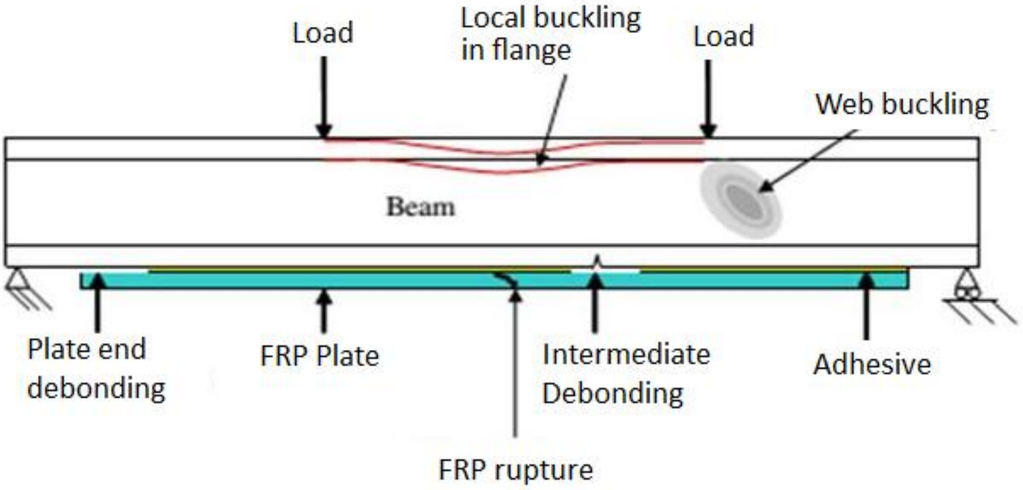


Figure 2.1: Failure modes of strengthened beam subjected to flexure

[J G Teng et al, 2012]

- Adhesive joint failure

‘Debonding’ (separation of FRP from the metallic substrate) frequently governs design. For metallic structures, failure occurs along the adhesive joint, unlike in concrete where failure occurs within the concrete substrate, along the flexural reinforcement.

- Tensile rupture of the FRP.

‘Rupture of FRP can be rare phenomena as the tensile strength of CFRP is more than steel. Usually it occurred after debonding as there is no composite action and sudden reduction stiffness.

- Tensile strength of the metallic member

The addition of FRP-strengthening changes the stresses within the metallic member, possibly increasing the tensile stress. For brittle cast iron members, failure is based on the extreme fiber stresses; a cracked section is not usually allowed (unlike for the design of concrete strengthening).

- Local buckling of the metallic member.

The metallic member should also be checked for local buckling in its strengthened state, for example, buckling of the compression flange or of the web in shear.

- Compressive strength of the existing structure.

The maximum compressive stress in the section may increase, resulting in a compression failure. If a steel beam is topped by a composite concrete slab, increased compressive stresses could lead to failure within the concrete (Sen et al, 2001: Tavakkolizadeh and Saadatmanesh, 2003).

- Compressive failure of the FRP

FRP strengthening is not usually used as compressive strengthening, as its compressive strength is limited by localized micro-buckling of the fibers and global buckling of the strengthened member.

2.1.5 Proven Applications of Strengthening Metallic Structures Using FRP Materials;

There are numerous applications where bonded FRP materials have been successfully used for repair and strengthening of metallic structures, typically those of steel or aluminum. Bonding of FRP materials to metallic structures was first used in mechanical engineering applications where the high cost of the fibers was not a significant drawback. Both the aerospace and naval industries have made use of CFRP materials for repair of fatigue damage to these structures. The offshore oil and gas industry has also made use of CFRP materials for enhancement in blast protection. Particularly noteworthy is the extreme environmental conditions these structures may be subjected to large changes in temperature for aircraft skins and salt-water spray for marine structures. CFRP strengthening of metallic aircraft structures that were defective, cracked or corroded have been shown to be a highly cost effective method for extending the service life and maintaining high structural efficiency. This has been shown by over 20,000 fatigue cracking or corrosion repairs being performed on Australian and US military aircraft, illustrating the acceptance of the technique in an application where safety and durability are critical (Aglan, H. A., 2002).

For naval applications, FRP strengthening is cost effective since the strengthening can be carried out from the most accessible side, and no stripping out of compartments in the immediate area of the repair is necessary. Welding also results in poor fatigue performance compared to bonding. These types of naval structures are subjected to cyclic stresses due to the wave loads, operational loading and mechanically induced loads from the propeller and engine forces that are transmitted to the structure (Grabovac, 1991). A reinforcement system by wet lay-up of CFRP material was developed to reduce the effect of cyclic stresses to prevent cracking of the structure.

2.1.6 Other Research on the Use of CFRP Materials for Strengthening Steel Structures:

While the focus of this research has been on the flexural strengthening of steel structures and the bond behavior for this type of application, there have been other applications that have shown promise for strengthening with CFRP materials. This includes methods of increasing the moment capacity of steel beam to column joints as well as techniques to prevent local buckling in thin-walled columns.

Teng et al (2012) demonstrated the effectiveness of confining circular steel tubes that have been restrained from buckling using GFRP wraps. The main parameter investigated was the number of plys used in wrapping the steel tubes. The experimental Test investigated the number of plys used in wrapping the steel tubes. Testing showed that the wraps were able to prevent the outward type of buckling exhibited by the control tube. While the ultimate load was only increased by 1 to 6 percent, the axial strain at the peak load was increased by a factor between 9 and 10. In addition, almost all of the beneficial effect of the wrapping could be achieved with only one ply of wrapping.

2.2 Bond Strength

Bonded joints are often the most effective way to join two different adherents, since the resulting stress concentrations at the joint are lower than for bolted connections. Furthermore, the anisotropic nature of most CFRP materials would preclude bolting as a connection method since the strength of these materials perpendicular to the fiber direction is relatively low, resulting in a tendency to split. To ensure full utilization of the applied CFRP material, a high degree of performance is necessary from the bond. Two basic requirements for good bond are, direct contact between the adhesive and the steel and CFRP substrates, as well as the removal of weak layers or contamination at the interface. A careful, meticulous approach is necessary when dealing with bonding since it may be difficult to verify that the quality of the bond and due to the local effect of bond stresses, any local defect of the bond may result in complete debonding of the applied strengthening material.

2.3 Summary

From review of existing literature it is evident that the technology is well established that design codes such as ACI440.2R-08 are available for strengthening of concrete structures. With the introduction of high-modulus CFRP materials, the possibility for providing a solution to the ongoing problem of infrastructure deterioration may be extended to steel structures as well. In case of steel structures, every section needs to be dealt independently due to its distinct cross sectional behavior under adverse loading, makes strengthening even more case specific.

Sen and Liby (1994) experimentally investigated the increment in strength and stiffness of strengthened steel concrete girders with CFRP. The authors studied experimentally the difference between improvement of ultimate flexural capacity of steel girders (I section beams) by using the high strength CFRP and high modulus CFRP. Authors found that 2mm thick high modulus CFRP shows more ductile behavior than 5 mm thick high strength CFRP. Depending on the yield strength of specimen and mode of failure, increase in ultimate strength observed ranged from 11% to 50%. This work was done with only longitudinal CFRP laminates.

Tavakkolizadeh and Saadatmanesh (2003), experimentally investigated the effect of thickness of CFRP (Longitudinal CFRP laminates) on increment of ultimate flexural strength of steel girders (I section beams). The authors established that as number CFRP layers increased the efficiency for utilization of CFRP sheet decreased.

Haedir et al (2006), experimentally established that for flexural strengthening of CHS (Circular Hollow Sections) beams number of fiber layers, their orientation and application procedure play a vital role. The authors observed through experimental evaluation of strengthened specimens that longitudinal fiber layers result in increase in moment capacity whereas transverse layers restrain or delay the buckling of the member.

The common parameter among reviewed research remained is strengthening of symmetric closed sections and use of longitudinal CFRP laminates. The literature review done shows that no or very little study has been done on stability or restraining of local buckling behaviour of closed and/or open sections strengthened with CFRP. No literature or past research meticulously studied the strengthening of open sections and their stability. Also there was no or very little research carried on changes in configuration of CFRP application (except Haedir et al, 2006). Therefore, there is need to study experimentally the advantage of strengthening of structural steel angle sections (open sections) with novel configurations to come up with whole new strengthening configuration to transform the behaviour as well as increase in strength of parent section in flexure.

Chapter 3

Experimental Program and Procedure

3.1 Introduction

The objective of the experimental program is to develop a system to study the increment in flexural strength and post strengthening behavior of bare structural steel angle sections by wrapping them with CFRP materials.

Carbon fiber used, is in the form of unidirectional CFRP strips. These sheets typically come with a width of 300 mm or 500 mm and are suitable when a wet lay-up process is necessary to conform to the exact surface configuration of the structure. The same fiber is also pultruded into unidirectional CFRP laminate strips. These strips are expected to be more suitable for field applications where a greater degree of strengthening is required and flat uniform surfaces are available for bonding.

The experimental program was conducted specifically in three groups

a. Fabrication of test specimens
b. Experimental test setup and Instruments organization
c. Experimental Results processing and interpretation

Fabrication of test specimens was divided into two sets; each set includes fabrication of 15 numbers of bare steel (control) specimens of desired configuration and then strengthening (using CFRP) of 12 control specimens with four different unique configurations (3 in each group). So in total 30 specimens fabricated.

First set comprised of 15 specimens divided into 5 distinct subsets, each having 3 specimens. 1st subset contains control specimens, 2nd subset contains single wrap (0^0), 3rd contains single wrap + hoop wrap ($0^0/90^0$), 4th contains double wrap + hoop wrap ($0^0/0^0/90^0$) and 5th contains externally bonded CFRP laminate (0^0). Approach of research was to transform the open section into closed section to study the increment in flexural strength and stiffness.

A unique symbol system was also developed to identify and code the specimens in order to have correlation with the experimental program and for ease of creating the data base. 30 specimens engineered and cut to desired size and then the layered supports are welded. All the specimens are grouped under the 2 sets and numbered from 1 to 30 and coded. Out of 30, 24 specimens strengthened using CFRP according to configurations mentioned earlier.

3.2 Angle Section

Equal angle sections (Structural steel) are used for experiments. All specimens are M/s Jindal Steel made. 30 specimens cut to 1.406 m length using cutting wheel. Measurement of sections with vernier caliper (least count 0.02 mm) it was found that the local made steel had more size variation than the M/s Jindal made. On meticulous observation of cross-sectional properties, it was confirmed that, there was no uniformity of size and angles are unequal according to their leg sizes (sizes checked at 1/3rd location to get minimum 3 values). But variation in length of legs was ignorable and classified them as equal angles only. Following table gives details of actual size.

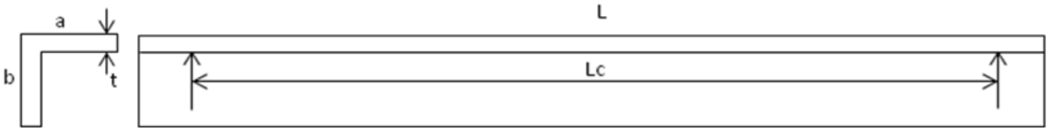


Table 3.1: Set A-Specimen Size data

Specimen No.	'a' in mm			'b' in mm			't' in mm			L in mm	Lc in mm
1	45.35	45.30	45.40	44.43	44.53	44.50	5.54	5.56	5.57	1406	1205
2	45.10	44.87	44.95	43.94	44.12	44.05	5.49	5.48	5.54	1406	1208
3	45.42	45.35	45.50	44.10	44.10	44.25	5.37	5.40	5.35	1405	1207
4	43.85	43.90	43.73	44.94	44.90	44.88	5.30	5.37	5.35	1406	1202
5	45.44	45.31	45.22	44.92	44.78	44.89	5.62	5.41	5.35	1408	1207
6	44.06	44.19	44.28	44.39	44.51	44.45	5.36	5.66	5.72	1407	1203
7	44.26	44.13	44.04	44.59	44.45	44.56	5.65	5.41	5.35	1408	1206
8	44.65	44.78	44.87	44.88	45.00	44.94	5.39	5.52	5.58	1408	1208
9	45.38	45.33	45.43	44.46	44.56	44.53	5.57	5.59	5.60	1406	1205
10	45.34	45.29	45.39	44.42	44.52	44.49	5.53	5.55	5.56	1406	1208
11	45.41	45.34	45.49	44.09	44.09	44.24	5.36	5.39	5.34	1405	1208
12	43.84	43.89	43.72	44.93	44.89	44.87	5.29	5.36	5.34	1404	1206
13	45.45	45.32	45.23	44.93	44.79	44.91	5.63	5.42	5.37	1405	1207
14	44.07	44.20	44.29	44.40	44.52	44.46	5.37	5.67	5.73	1406	1202
15	44.32	44.19	44.10	44.65	44.51	44.62	5.71	5.47	5.41	1408	1210

Table 3.2: Set B-Specimen Size data

Specimen No.	'a' in mm			'b' in mm			't' in mm			L in mm	Lc in mm
16	50.28	50.43	50.54	49.88	50.03	50.14	5.10	5.19	5.13	1405	1208
17	50.35	50.50	50.61	50.72	50.38	50.49	5.23	5.14	5.20	1404	1206
18	50.45	50.45	50.36	50.41	50.27	50.38	5.18	5.15	5.09	1408	1210
19	49.82	49.95	50.04	50.60	50.72	50.66	5.22	5.29	5.35	1406	1208
20	50.56	50.43	50.34	50.57	50.43	50.54	5.43	5.54	5.48	1409	1208
21	49.21	49.34	49.43	50.74	50.86	50.80	5.23	5.30	5.36	1405	1206
22	50.04	49.91	49.82	50.17	50.03	50.14	5.18	5.03	4.97	1404	1205
23	51.66	51.79	51.88	48.20	48.32	48.26	5.33	4.95	5.01	1406	1206
24	50.27	50.42	50.53	49.87	50.02	50.13	5.09	5.18	5.12	1406	1208
25	50.34	50.49	50.60	50.71	50.37	50.48	5.22	5.13	5.18	1408	1207
26	50.44	50.44	50.35	50.40	50.26	50.37	5.17	5.14	5.08	1407	1203
27	49.84	49.97	50.06	50.62	50.74	50.67	5.24	5.31	5.36	1409	1208
28	50.55	50.42	50.33	50.56	50.42	50.53	5.42	5.53	5.47	1405	1206
29	49.46	49.59	49.68	50.99	51.11	51.05	5.48	5.55	5.61	1408	1206
30	50.06	49.93	49.84	50.19	50.05	50.16	5.20	5.05	4.99	1408	1208

Table 3.3, provides the details of section classification based on buckling class as per IS800. It can be observed that the sections are semi Compact and hence do not undergo local buckling.

Table 3.3: Classification of Section based on buckling class

Specimen	a or b	t	b / t	Total no.	As per IS800:2007 : Cl. No. 3.7.2 and 3.7.4
A45T5	45.00	5.00	9.00	3	Semi Compact
A50T5	50.00	5.00	10.00	3	Semi Compact

A-Angle; t-Thickness; b-Width; All dimensions are in mm (UN)

3.3 Properties of carbon fiber used

Table 3.4 represents the mechanical properties of carbon fibers supplied by manufacturer. According to Fig.3.2, the fibers can be classified as high strength fibers.

Table 3.4: Mechanical Properties of Carbon Fibers supplied by manufacturer

Fiber Type	Item / Unit	Number of Filament	Tensile strength in MPa	Tensile Modulus in MPa	Density (g/cm^2)	Elongation (%)	Filament Diameter (µ)
TC-35	12K	12000	4000	240	1.8	1.6	7

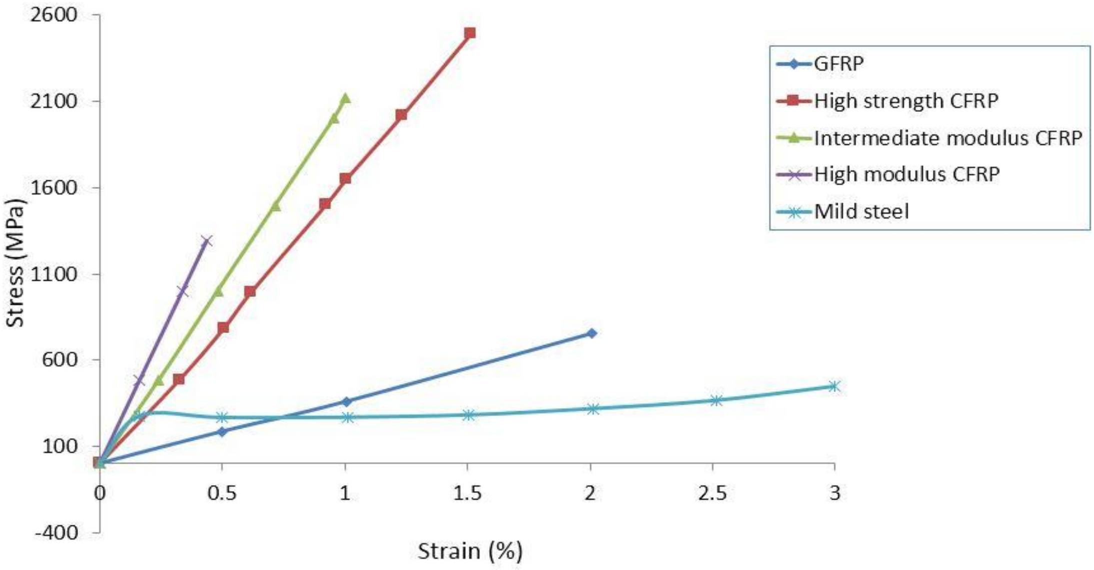


Figure 3.1: Classification of Carbon fibers

[J G Teng et al, 2012]

3.4 Adhesive Properties

Epofine-556 resin and finehard-951 are used as hardener. The resin and hardener are mixed to 10:1 proportion to prepare the adhesive as per manufacturer's reference. As mentioned earlier in the introduction, adhesive properties are kept constant throughout the experimental program and study of its chemical properties is not in scope this report.

3.5 Test Matrix

The test specimens were labeled such that the type of material, nominal dimensions of the specimen, grouping, type and number of CFRP layer can be identified from the label. Following Table 3.5; provides the nomenclature further used to refer flexural test specimens in this report.

Table 3.5: Test Matrix

	Code	CFRP wrap Configuration	a or b in mm	T in mm	Specimen No.	Total
Set-A	A45T5	Control Specimen	45	5	1 to 3	3
	A45T5C1	($0^0/90^0$)			4 to 6	3
	A45T5C2	($0^0/0^0/90^0$)			7 to 9	3
	A45T5CR	Bonded laminate			10 to 12	3
	A45T5C0	(0^0)			13 to 15	3
Set-B	A50T5	Control Specimen	50	5	16 to 18	3
	A50T5C1	($0^0/90^0$)			19 to 21	3
	A50T5C2	($0^0/0^0/90^0$)			22 to 24	3
	A50T5CR	Bonded laminate			25 to 27	3
	A50T5C0	(0^0)			28 to 30	3

A-Angle; T-Thickness; b-Width; All dimensions are in mm (UN); C1- single wrap + hoop wrap ($0^0/90^0$); C2- double wrap + hoop wrap ($0^0/0^0/90^0$); C0- single wrap (0^0); CR-Externally bonded CFRP laminate (0^0) (0^0, Skin strengthening);

3.6 Fabrication of test specimen

3.6.1 Tensile coupon test specimen

Four tensile coupons were taken out from the middle of the control specimens and as per ASTM-E8/E8M-13a. Table 3.6 provides the details of specimen sizes.

Table 3.6: Tensile Coupons specimen size data

Specimen No	Width in mm	Thickness in mm	Guage Length in mm	Grip Width in mm	Total Length in mm
1TC	12.59	5.49	60.00	19.88	201.00
2TC	12.45	5.27	60.00	20.22	201.00
3TC	12.81	5.04	60.00	20.31	201.00
4TC	11.63	4.90	57.00	19.20	197.00

1,2,3 - Number; TC-Tensile Coupon;

Figure 3.3 and 3.4 explain the fabrication of the coupons on EDM machine facility at IIT Hyderabad.

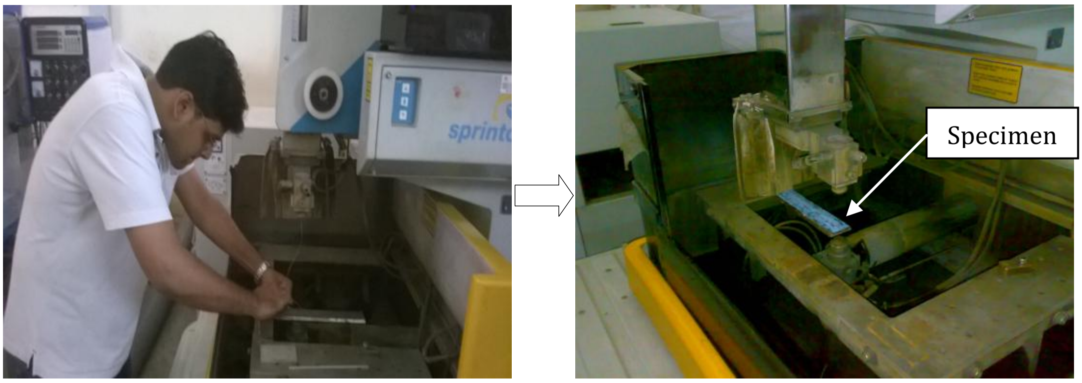


Figure 3.2 : Adjustments and fixing of specimens inside EDM machine

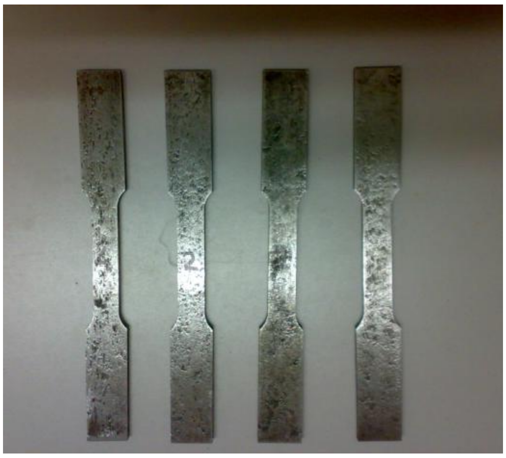


Figure 3.3: Finished tensile test coupons

3.6.2 Flexural test specimen

Literature review indicates that there are no specific guidelines available regarding sizes, length for flexural testing of structural steel. Since the transmission towers are typically made up of 1-2 m long angle sections, it was decided to test the specimens of length 1.406 m with distance between supports as 1.206 m.Thorough thinking and some stability tests made at structural engineering lab for deciding the support system for the angles for testing them on flexure test machine. Initially it was decided to go for vertical plate’s support system, on trial test it was observed that the angles may not be stable and possible splitting of support may result in yielding of support before the specimens itself or angle section may lose contact with roller support under it due to slip in longitudinal direction. Then some tests made with layered welded support system which found stable over vertical plate supports, delivered expected stability and safety. Though it would be a restrained bending it resulted in safest and stable support system. Layered support system required less cutting, grinding and welding efforts as compared with former vertical plate support system. All specimens cut to desired size, grinded and welded. Below Fig. 3.5 and 3.6 schematically describes the support system fabricated specifically for the testing of angle sections. Support system has been developed by keeping in mind, the specimen should be stable under loading and there should not be wear and tear of roller supports of bending equipment. Also due importance was also given to the slip of the specimen from the rollers by keeping the base length of 100 mm. This will adjust as the specimen will start rotating around the contact support roller.

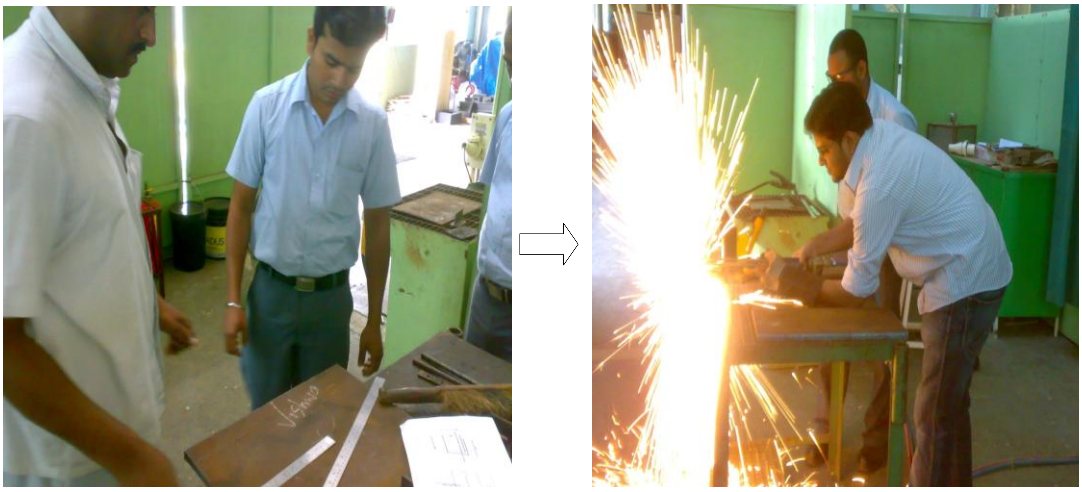


Figure 3.4 : Measurement and marking and gas cutting of plates

Figure 3.5 : Grinding of plates and intermittent welding

3.7 Methodology for application of CFRP

3.7.1 Introduction

On reviewing various ways of FRP application to structural steel as well as concrete structures, it is observed that, little research has been carried on strengthening of angle sections and those who have started working are still following the externally bonded method of strengthening. In this research work an attempt has been made to develop a unique CFRP wrap system. Open angle section is transformed into closed sections by providing stacked cardboard sheets as an internal formwork and then CFRP is wrapped around to give it square shape. Following fig shows the innovative idea that has been proposed to strengthen angle sections.

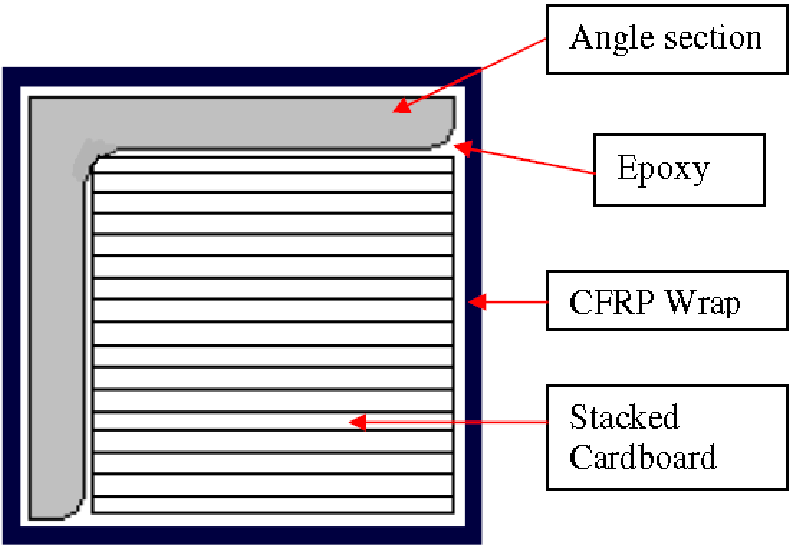


Figure 3.6 : Schematic view of angle section with stacked cardboard and CFRP wrap

Initially, in place of cardboard other options were analyzed and tried like wooden block, thermocol, foam and aerosol etc. It was found that bringing these options in practicality would be difficult. Also wood could result in another load carrying member and whole purpose of strengthening with CFRP will go in vain. So to find easiest way of making formwork to give shape to the CFRP, it was decided to go for stacked cardboard sheets cut to desired size as per angle section dimension. Stacked cardboard will take part in load sharing but comparatively load carried by it will be negligible because of its brittle property and a discontinuity created exactly at the center of its span.

3.7.2 Surface Preparation

The purpose of surface preparation is to remove contamination and weak surface layers, to change the substrate surface topography and/or introduce new surface chemical groups to promote bond formation. An appreciation of the effects of surface preparation may be gained from surface analytical or mechanical test techniques. Surface preparation generally has a much greater influence on long-term bond durability than it does on initial bond strength, so that a high standard of surface preparation is essential for promoting long-term bond integrity and durability (Mays and Hutchinson, 1992).

In strengthening applications the parent material must be treated in situ, generally under less than ideal conditions. The plane of the surface(s) to be treated (horizontal, vertical, overhead, etc.) has a large bearing on the selection of an appropriate method. The choice of method, or combinations of methods, depends upon the costs, the scale and location of the operation, access to equipment, materials and health and safety conditions. The composite reinforcement may be provided in a variety of forms, but prefabricated elements and pultruded profiles can be treated off site. This has great advantages because anything treated in a factory environment can be dealt with in a more reliable way than on site. Following table gives details of degree of suitability of surface bonding and pretreatment required. It can be clearly seen that CFRP can bond to steel through an adhesive.

Table 3.5: Surface treatment requirement

Material	Suitability for Bonding	Pre-treatment required
Cast iron	* * * * *	Cursory
Steel	* * * *	Straightforward
Stainless steel	* * *	Quite Demanding
Zinc	* * *	
Aluminium	* * *	
Concrete	* * * *	Straightforward
GFRP	* * * *	
CFRP	* * *	
PVC	* *	Rigorous
Polyolefin	*	Complex

[Hollaway and Teng, 2012]

The methods of surface preparation can be considered under four categories (Brewis, 1982):

1. Solvent degreasing
2. Mechanical techniques
3. Chemical techniques
4. Physical techniques

The most appropriate method, or combination of methods, depends upon the nature of the substrates, but an indication of the general requirements is given in above Table 3.7. Solvent degreasing removes grease and most potential contaminants. The choice of solvent should be based on the principle that ‘like dissolves like’, although toxicity, flammability and cost should be taken into consideration. A volatile solvent such as acetone should always be chosen or else any residues may form a weak surface layer. For metallic substrates, alkaline cleaners and/or detergent solutions are often advised after solvent treatments, to remove dirt and inorganic solids. They may also be used instead of solvents for health and safety reasons, but should be followed by thorough rinsing and drying in hot air prior to bonding.

Mechanical treatments often cause much obvious roughening of a surface but the effect on adhesion is complex. It should be remembered that a rough surface per se is not a fundamental requirement for adhesion. The most important requirement of mechanical treatment is to remove weak surface layers and to expose a clean, new surface. The various mechanical methods depend on the abrasive action of wire brushes, abrasive pads and wheels, blasting media and tools such as needle guns. Two major aspects are control of the method and assessment of the surface following treatment.

Chemical and electrochemical methods typically cause more complex changes to surfaces than do mechanical methods. In addition to the cleaning action and removal of weak layers, chemical treatments often roughen a surface microscopically. Anodizing, for example, results in a very porous surface, and other techniques for metals result in a micro-fibrous topography. Treatments are designed to result in the formation of stable and coherent oxide structures. However, a significant disadvantage of chemical methods is the toxicity of the materials used and the subsequent waste disposal problem. Physical methods include techniques that promote a strong oxidizing reaction with the surfaces of materials. These include factory-based techniques such as flame treatment and corona discharge. They are very effective on inert plastics like polypropylene but also work well on thermoset-matrix composites. Flame treatment has also been applied to timber surfaces, albeit in the context of factory-based processes for painting and coating.

Procedure for surface preparation of specimens employed as follows,

Cleaning of work piece

With the help of wire brush, angle sections were cleaned to remove the loose rust, dust etc. Acetone was used to clean the surface thoroughly. Then with dry piece of cotton specimens were dried to remove any moisture. Fig. 3.8; shows details of cleaning.

Figure 3.7 :cleaning of specimen by wire brush

Numbering the Specimens

For better coding and identification of the specimens, they have been numbered from 1 to 30 in correlation with their identification and stored data. After painting, specimens were kept for drying in lab environment for 4 hours.

Figure 3.8 : Coding of specimens

3.7.3 Fabrication of formwork

1. Cutting of cardboard

Before cutting of cardboard to exact size, the angle specimen cross-sections were re-measured and reconfirmed their dimensions with earlier data stored. Then with high quality scissor cardboard cut to desired sizes. Then the strips of cardboard stacked/glued together with very little quantity of glue approximately 2ml per 100 mm spacing. Below picture explains this

Figure 3.9 : Marking and cutting of cardboard

2. Attachment of formwork

Stacked cardboard formwork of desired size was then glued to angle section as shown in Fig. 3.11

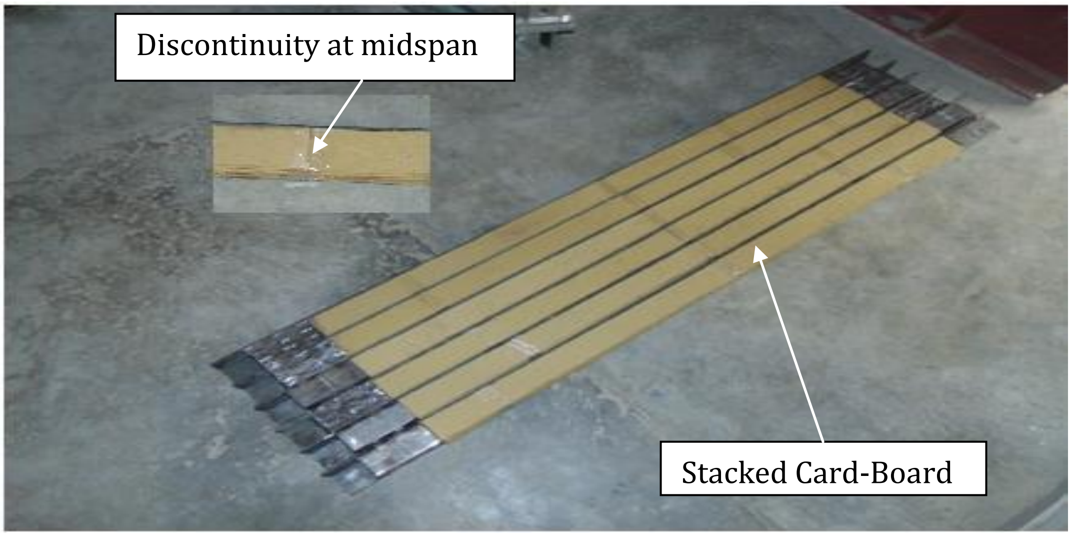


Figure 3.10 : Attachment of formwork

3.7.4 CFRP Wrapping scheme

1. Surface preparation

Before application of CFRP, once again the steel surface was sanded up by using 100 grain size grit sandpaper for achieving uniform steel surface. Also the cardboard surface on layered side was sanded by the grit sandpaper for uniform surface.

Figure 3.11 : Surface preparation before application of CFRP

2. Cutting of carbon fiber sheet

With the help of high quality scissors the carbon fiber strip was cut to desired size (perimeter of each closed angle section) as shown in fig. no. 3.13. Care was taken to avoid any direct contact of the CFRP with skin as while cutting the fibers there is possibility of inhalation of carbon molecules. Following precautions were taken while working with CFRP which are bound to be mentioned.

a. Protect your skin! CF is a skin irritant that can provide red rashes and some degree of pain. Use gloves, and wrap your face up if you feel that you need to. Wash your hands or take a bath before taking food.
b. Work in a well-ventilated area! CF dust is very hazardous to your lungs! Do not try to cut without good ventilation.
c. Eye protection can be provided by standard safety glasses with side shields for non-machining work.

Figure 3.12 :Marking and Cutting of CF sheet

3. Setup for CFRP wrapping

Following Figure describes the open setup created for easy wrapping and curing of specimens. Three supports at spacing of 1.3 m kept in line for proper handling of the specimens.

Figure : Setup for wrapping system

4. Making of epoxy

The required quantity of carbon fiber sheet per specimen was cut and weighed on digital weighing balance of 0.001g accuracy. Then resin of same weight as of CFRP was taken and mixed with hardener in proportion of 10:1. Care was taken to avoid bubble formation by thoroughly and gently mixing resin with hardener. Mixing time ranged from 10 to 15 minutes as per quantity. Care was taken to avoid solidification of mixture in paper made beaker if it is mixed for long period of time. Eco-friendly paper made beakers/cups were used for mixing of resin and hardener as those can be thrown away after use.

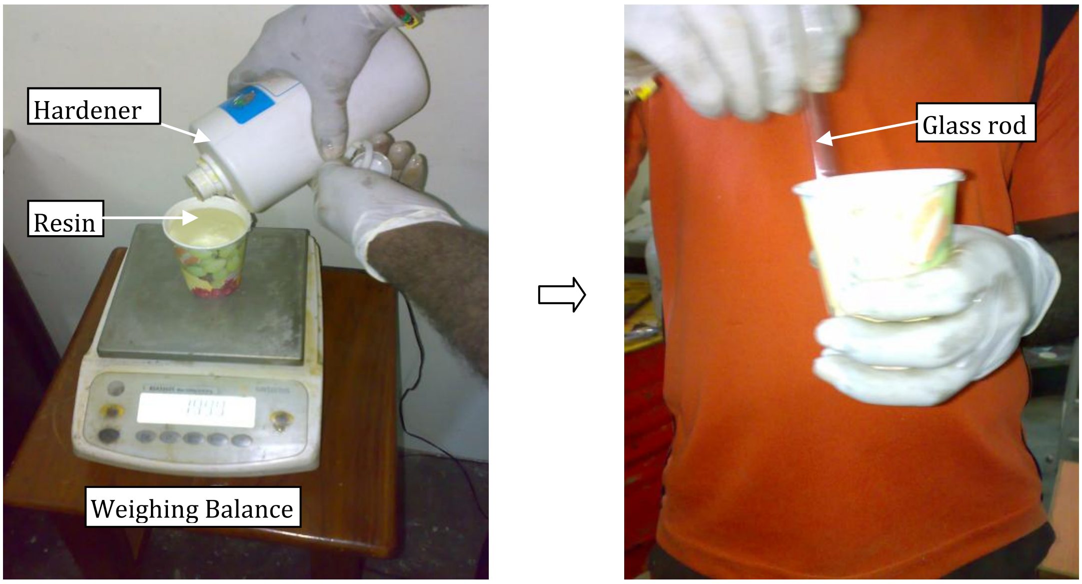


Figure 3.13 : Weighing and Making of epoxy

5. Wrapping of CFRP

Immediately after mixing resin and hardener, the uniform layer of approximately 0.5 mm thick mixture was applied to the steel face of specimen with the help of high quality fiber hair brush 50 mm wide. Then carbon fiber sheet placed on the steel surface in desired direction as per the test matrix and then rolled with Teflon rollers for uniform epoxy application and removing the excess. Care was taken to avoid any air-entrapment which can reduce the bonding. Same process then followed for all the four faces. It was observed that there was soaking of epoxy by the cardboard sheet and reported the same as shortcoming of using the cardboard. In this way other specimens were wrapped according to their matrix configuration. Single specimen required approximately 1 hour for wrapping of single layer. After single wrap the specimen was kept for 15-25 minutes for curing and then again second, third consecutive wraps as per individual configurations were given. Then the wrapped specimens were kept in the lab environment for curing for 24 hours. Care was taken not to hold the specimens at its center to avoid possible induction of residual stresses. Fig. nos. 3.16 to 3.19, describes the whole wrapping scheme. Care was taken to avoid any skin contact of resin and hardened resin was disposed off immediately after wrapping without solidifying of brush.

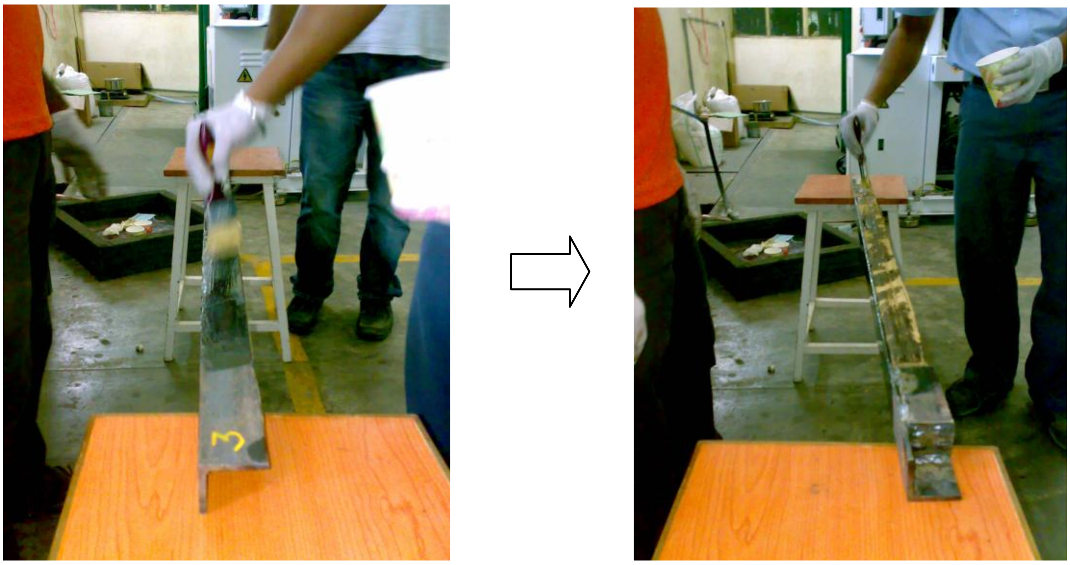


Figure 3.14 : Application of epoxy to specimen

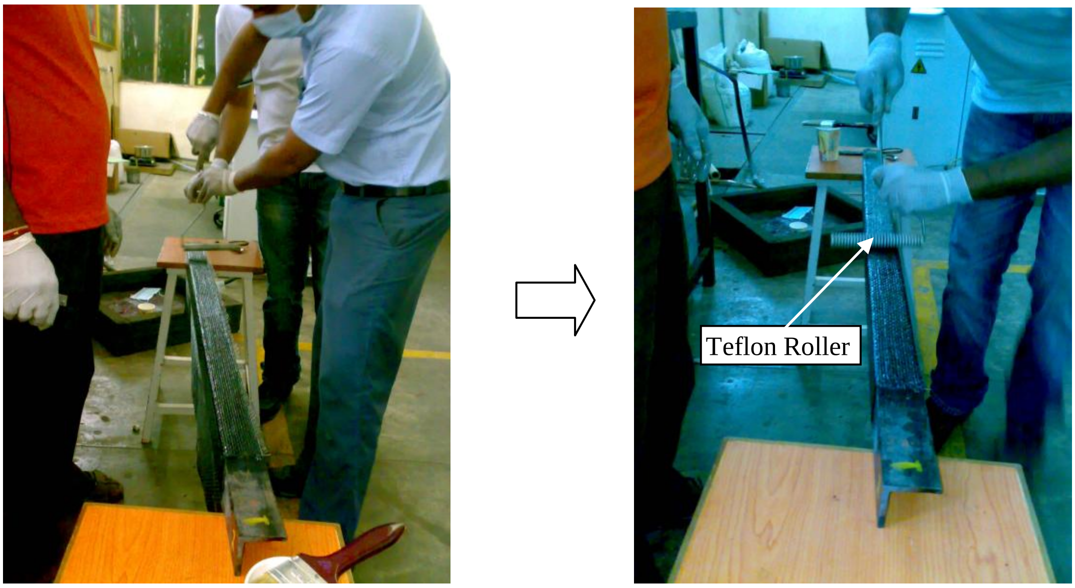


Figure 3.15 : CFRP wrapping (single layer unidirectional)

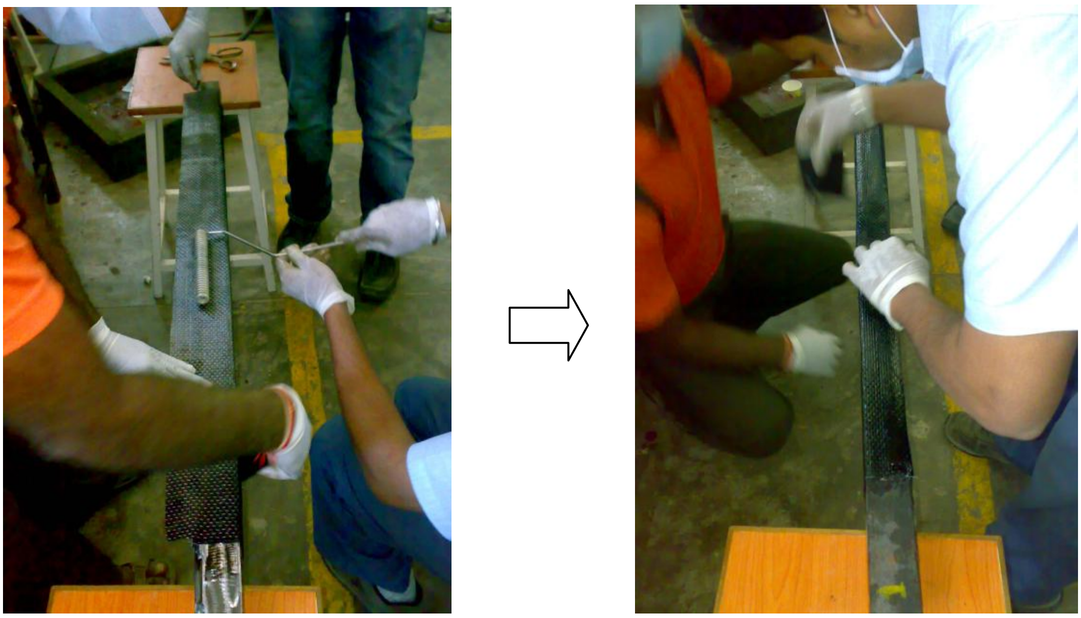


Figure 3.16 : CFRP wrapping (Second layer unidirectional)

Improvement in wrapping scheme by wrapping of 3 specimens simultaneously in 1 hour. It saved the adhesive as well as time.

Figure 3.17 : Assembly line for CFRP wrapping

3.8 Experimental test setup

3.8.1 Test Setup for Four Point Bending

A computer-controlled MTS Landmark®, servo-hydraulic testing actuator series 244 (actuator capacity = 250 kN; Structural Engineering lab, Civil dept, IIT Hyderabad) used for four point bending test. Displacement control was used to drive the hydraulic actuator at a constant speed of 0.1 mm/sec for all tests. Fig. 3.20 and 3.21, provide information about the MTS actuator, its fixtures and preliminary adjustments with the spreader beam. Hinge supports were simulated by full rounds visible in the Fig. 3.22. Load was applied through Load rollers uniformly, through single line contact as line udl (uniformly distributed load). Specimen is seated over two support rollers (single line contact) 1.206 m away from each other. Two LVDT transducers, M/s HBM made were used record vertical (LVDT-1) and horizontal

(LVDT-2), midspan deformation. Perspex (acrylic sheet) strip of 5 mm thick and 25 mm wide was used as an attachment to access the LVDTs as shown.

Figure 3.18 : Tightening of actuator fixtures

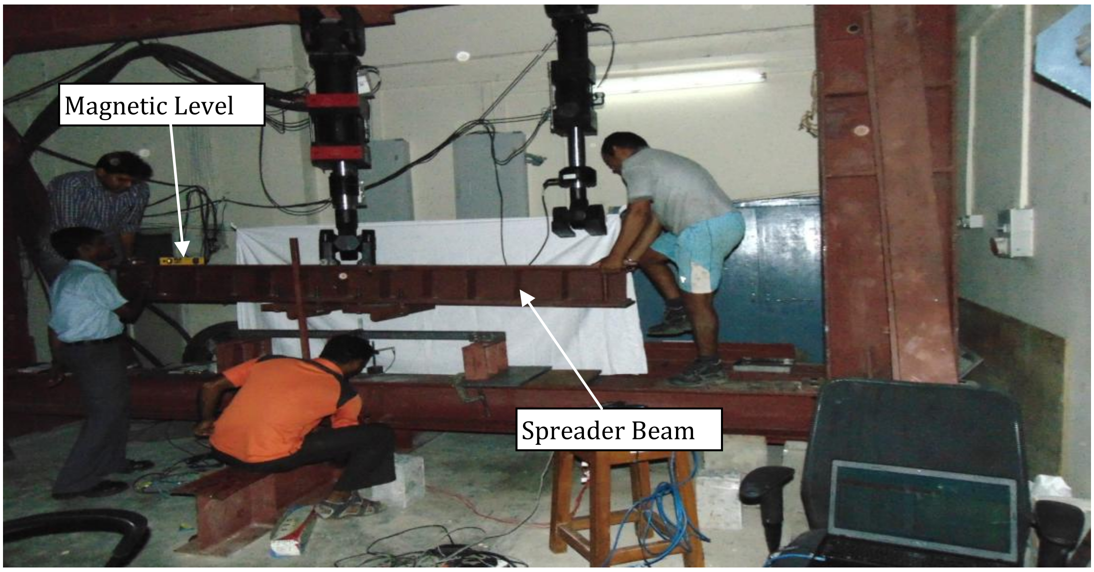


Figure 3.19 : Leveling of spreader beam and Alignment of Actuator

HBM data acquisition system MX840 and MX1615 (16 pin connector) used to record strains, corresponding load increments and displacements. Fig. 3.24 and 3.25 shows the ready instrumentation before commencement of every test.

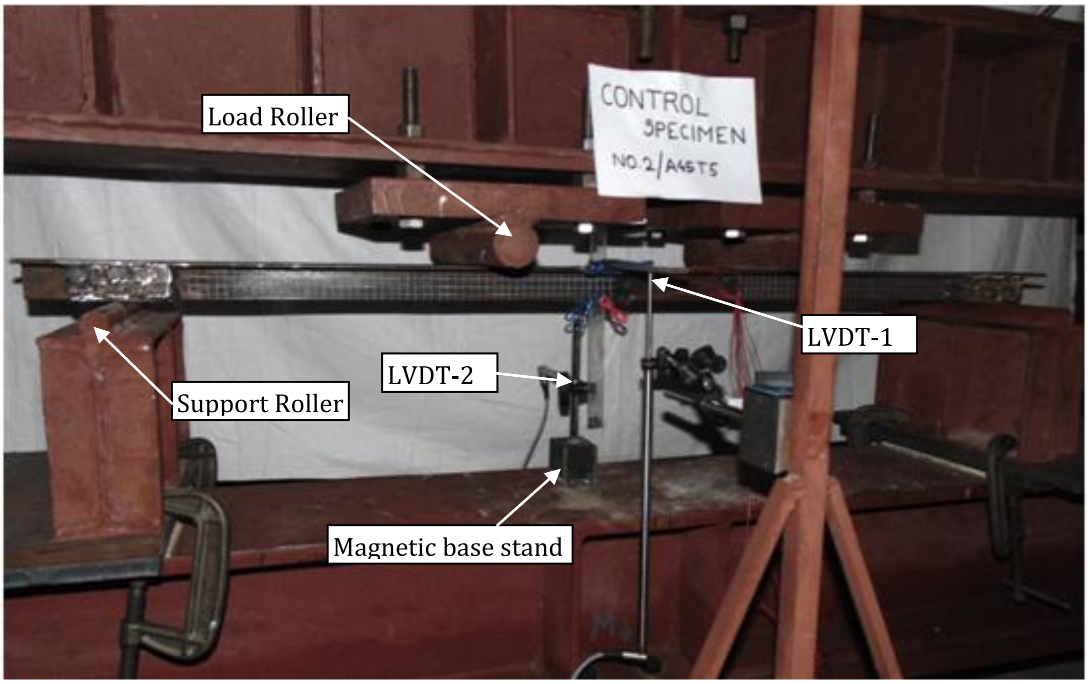


Figure 3.20 : Four point bending experimental test setup

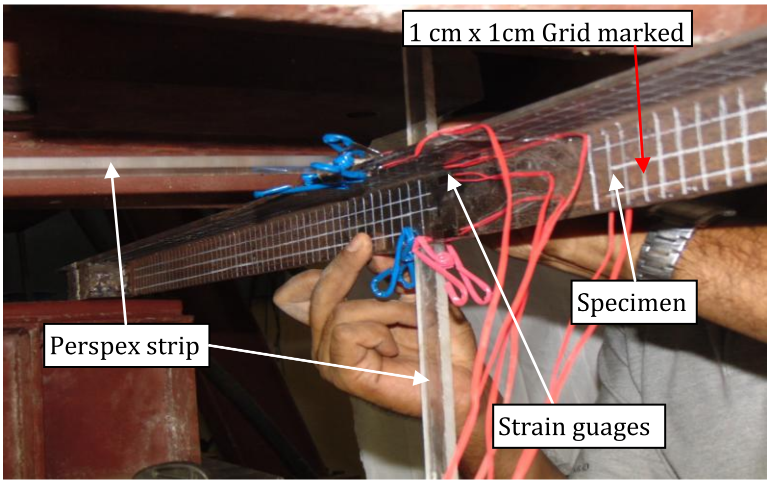


Figure 3.21 : Perspex Strips attached to specimen and clamped in place

Figure 3.22 : Instrumentation in place

Figure 3.23 : HBM DAQ and HBM Controller Computer

3.8.2 Strain gauge installation

TML Linear strain guage type: FLA-6-350-11 (350 ohm resistance) used for recording the strains, supplied by M/s Tokyo Sokki Kenkyujo., ltd. Type P-2 Adhesive used for application of strain gauges to the specimens. Basic bonding procedure (given by supplier) for application of gauges was followed. For control specimens 6 strain gauges (Type-1) (Locations 1, 2, 3, 4, 5 and 6) used to capture the strains at extreme fibers of specimen midspan. Fig. 3.26 and 3.27, briefs the location of strain gauges.

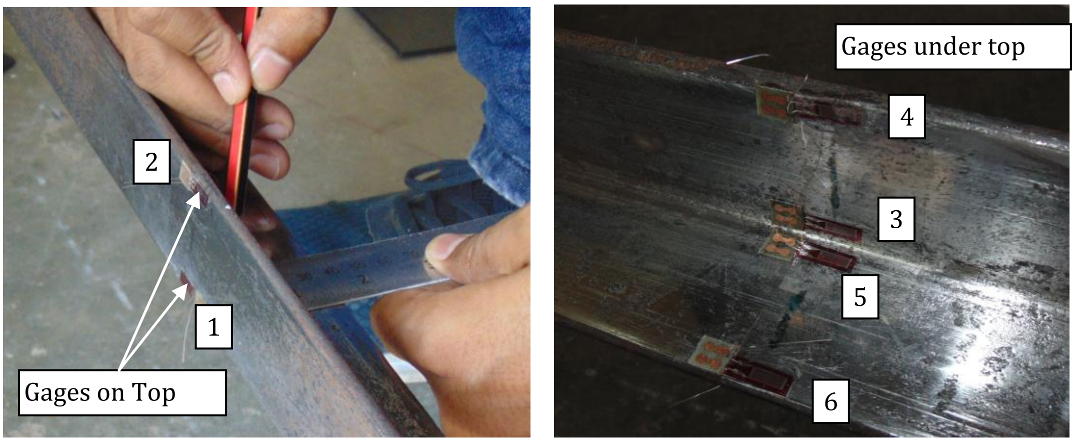


Figure 3.24 : Strain guage location Type-1

For wrapped specimens, 4 strain gauges (Type-2), on top (S1 and S2) and bottom (S3 and S4) attached to capture the strains at extreme fibers of specimen midspan. Fig. 3.27 briefs the location of strain gauges.

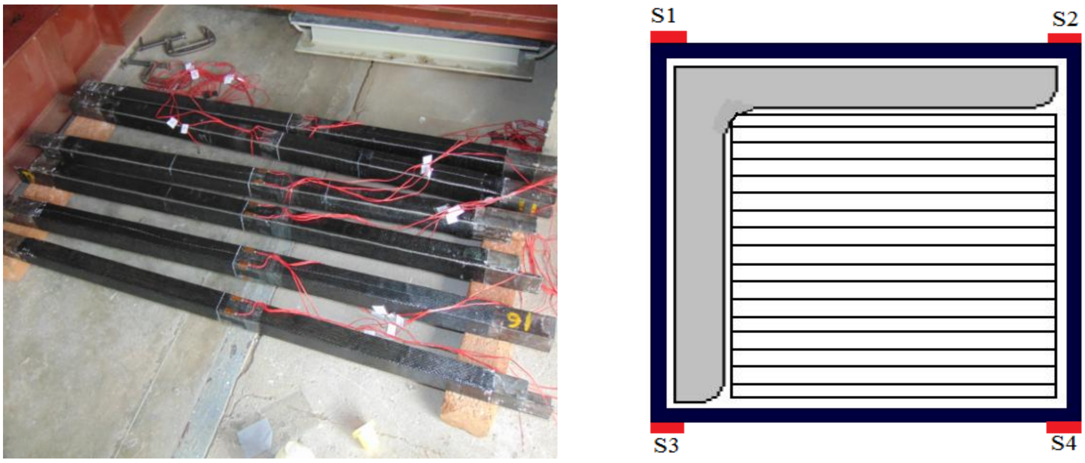


Figure 3.25 : Strain guage location Type-2

3.8.3 Test setup for Tensile coupon test

A typical experimental setup was used for tensile test of coupons is shown below. It is computer-controlled MTS Landmark® servo-hydraulic cyclic test machine of capacity 100 kN (Engg. Optics Lab, Dept. of Mech. Engg, IIT Hyd). The coupons were tested axially under displacement control, loaded at a rate of 1 mm/min. MTS Extensometer 20mm guage was used to get the elastic region behavior and the value of elastic modulus. Fig. 3.28 and 3.29, explains the setup.

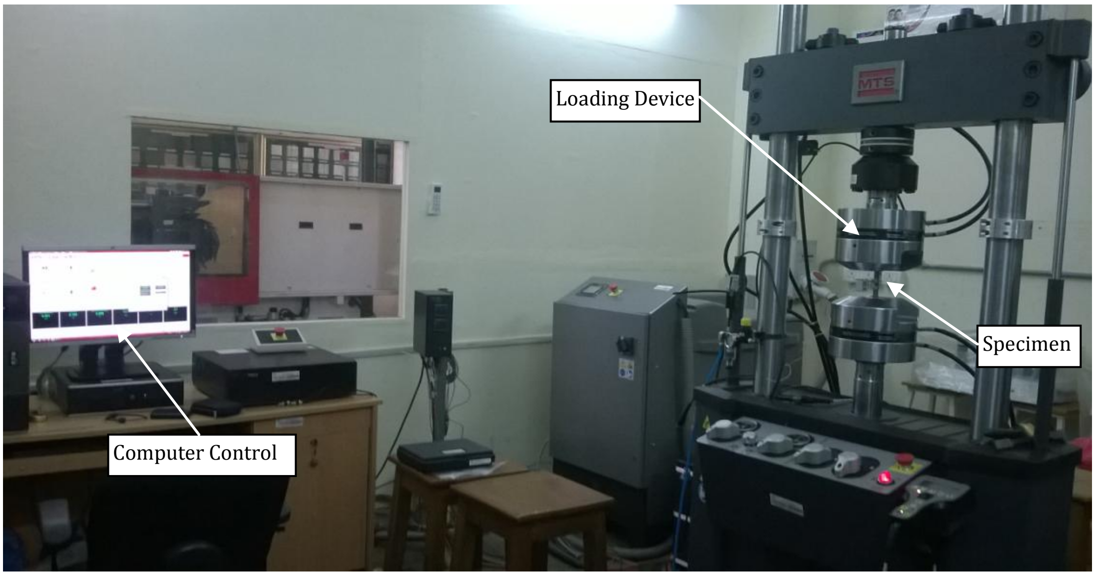


Figure 3.26 : Tensile Test Setup

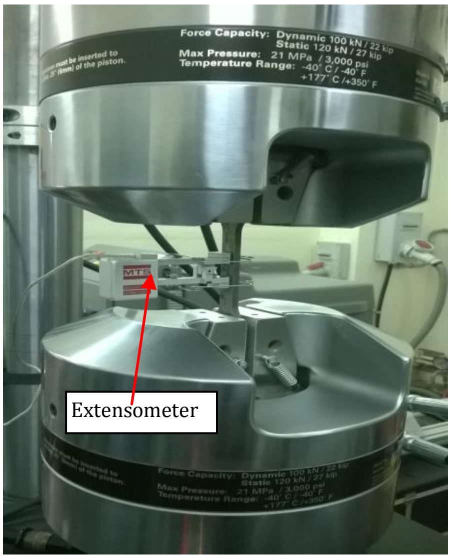


Figure 3.27 : Tensile specimen with extensometer attached

Chapter 4

Experimental results

4.1 Introduction

The experimental program was carried out in two phases (each with five subsets) that led to the development of a strengthening system for steel angle section. Four different types of CFRP bond strengthening configurations were selected and tested experimentally. The experimental testing involved arriving at an ideal displacement rate which was accomplished by trial testing of steel beams (without strain gauges).. Displacement rates of 0.05 mm/sec and 0.1 mm/sec were selected as both gave almost similar results. However, the displacement rate of 0.05 mm/sec resulted in collection of large amount of data which may not be necessary. Therefore, the testing of the specimens was carried out with a displacement rate of 0.1 mm/sec. This chapter discusses the failure modes observed, Load vs Deformation (vertical and horizontal), variation of ultimate load and Moment vs Strain for control and CFRP bonded specimens subjected to four point bending. Also this chapter presents results of material characterization of structural steel used.

4.2 Failure modes

4.2.1 Control Specimens

A steel angle section subjected to bending can fail in one of the following ways:

1. Flexural Buckling (FY)
2. Lateral Torsional Buckling (LTB)
3. Local Buckling (LB) of elements of the section
4. Yielding due to flexure
5. Combination of above

4.2.2 Control specimen testing Subset-1 (A45T5 and A45T5)

The failure modes observed during testing of control specimens (bare steel angle section without CFRP wrap) are shown in Table 4.1. It can be observed that a majority of the sections failed due to combination of LTB and FY. This may be due to bowing and twisting of the angle section as soon as it is loaded due to unsymmetrical bending.

Table 4.1: Failure modes observed for control specimen

Specimen No.	Code	Shear failure	Reaching Full plastic moment capacity (Mp)	Lateral Torsional Buckling (LTB)	Local Buckling (LB)	Flexural yielding (FY)
1	A45T5	x	x	√	x	√
2		x	x	√	x	√
3		x	x	√	x	√
16	A50T5	x	x	√	x	√
17		x	x	√	x	√
18		x	x	√	x	√

Figures 4.1 to 4.5 shows the failure modes observed for control specimens.

Figure 4.1 : Control specimen under four point bending

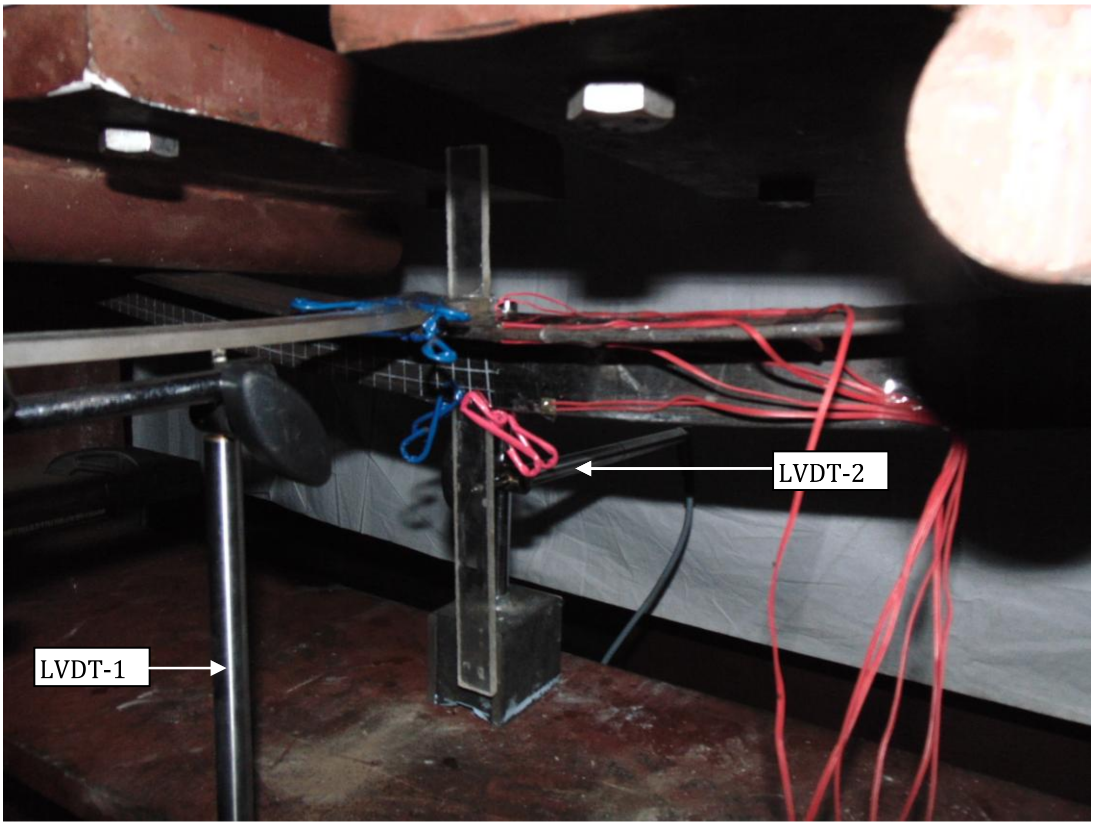


Figure 4.2 : View of Flexural Yielding (FY) with vertical LVDT-1 fully pressed

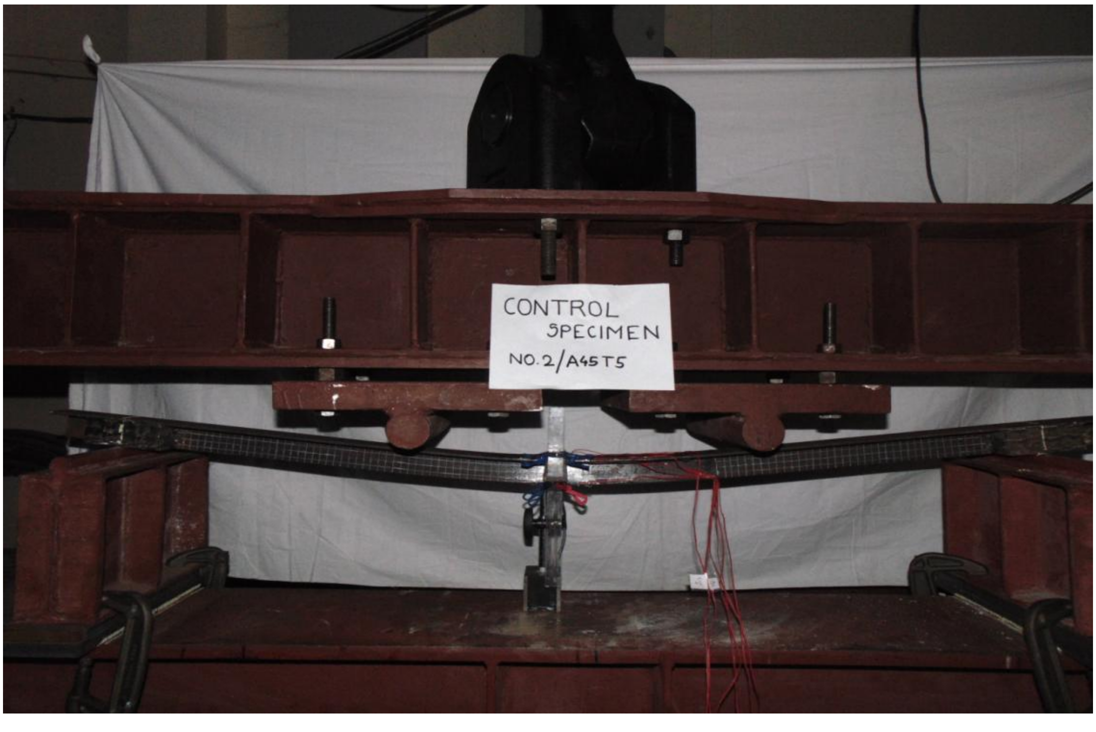


Figure 4.3 : View of Flexural Yielding (FY)

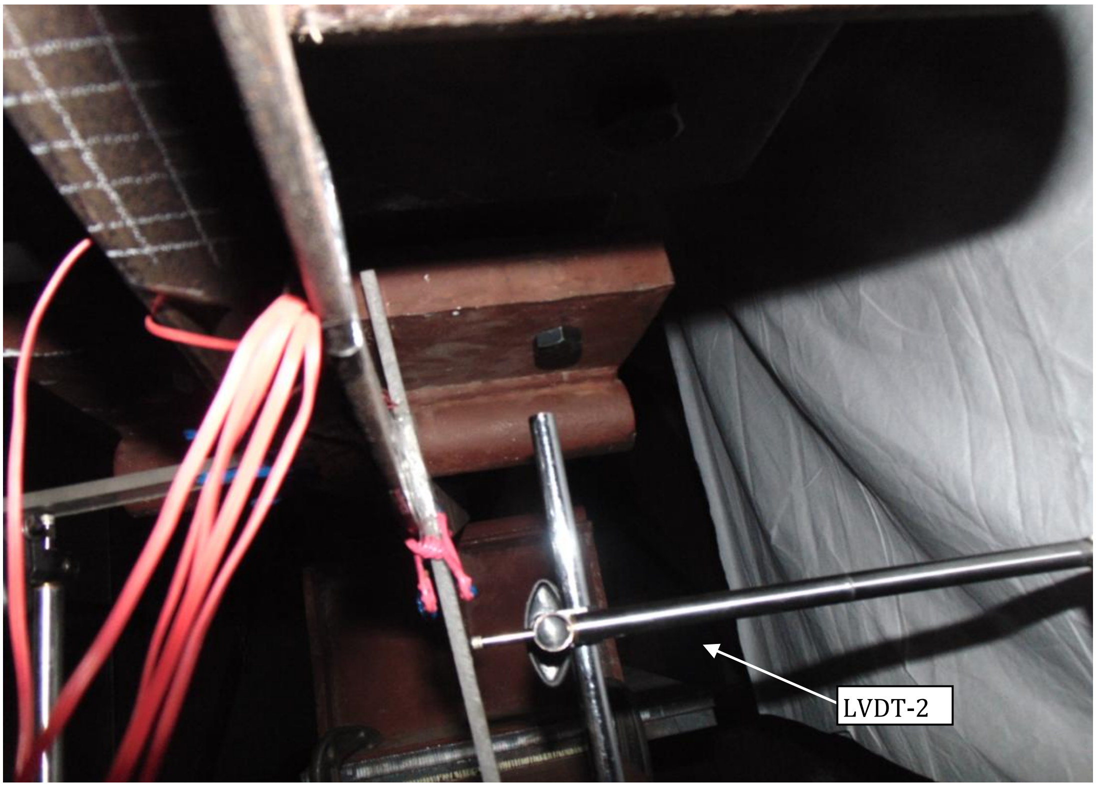


Figure 4.4 : Lateral Torsional buckling (LTB) with horizontal LVDT-2 pressed

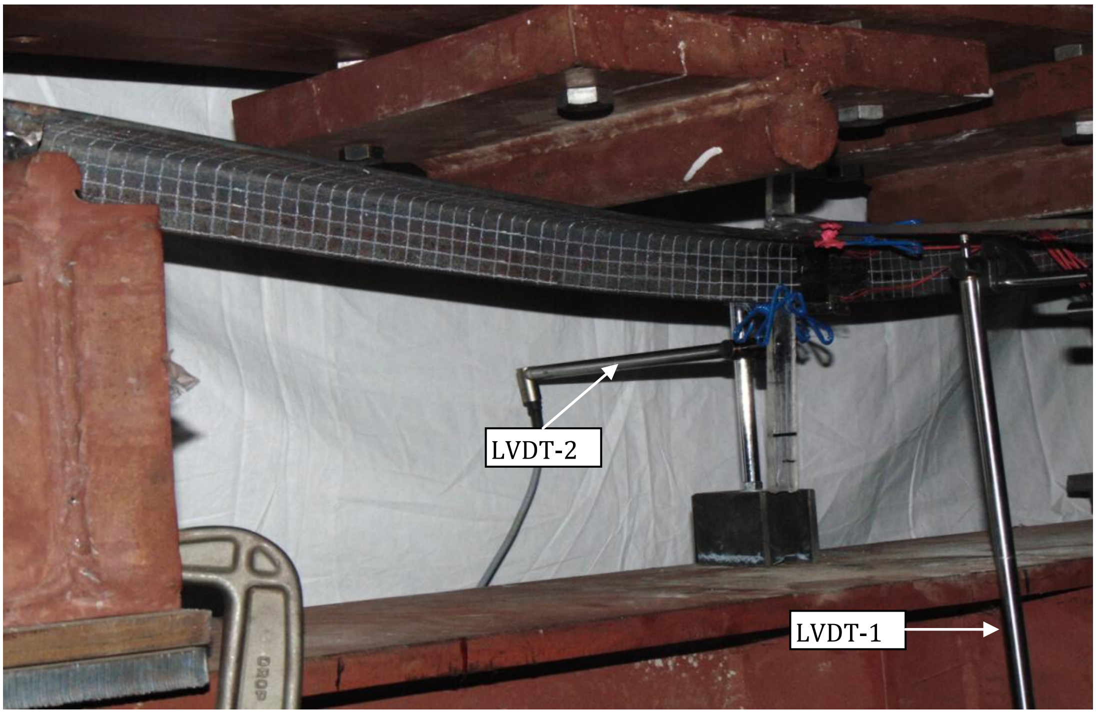


Figure 4.5 : Set B; View of Flexural Yielding (FY) with vertical LVDT-1 fully pressed

4.2.3 Strengthened Specimens Subset-2 (A45T5C1 and A50T5C1)

Improvement in the behavior of wrapped specimen of this subset over control specimen was observed; up to approximately vertical displacement of 20 to 25 mm all strengthened specimens shown transformation of [FY + LTB] into FY only. For specimens 4 and 19, debonding and delamination predominantly started in flexural-shear zone. This is because of quality control shortcoming as at the time of wrapping of specimens, Teflon rollers got solidify which reduced the efficiency of rolling resulted in air entrapment lead to weak bonding or formation air voids. For other wrapped specimens debonding and delamination started in flexure zone as the quality control measures were taken care by cleaning of rollers at time of wrapping. No visible rupture of CFRP observed for any sample for subset-2(except for No.19) due to the fact that specimen 19 was found to be the properly wrapped among the subset-2 which resulted in strong bond. At the time of testing cracking of bond for initial 0^0 CFRP wrap was observed. Table 4.2, reports the observed failures for CFRP wrapped specimens. Figures 4.6 to 4.11 shows the failure modes observed.

Table 4.2: Failure modes observed for subset-2

Specimen No.	Code	Steel and adhesive interface debonding	Adjacent CFRP interface debonding in		CFRP delamination	CFRP rupture
			Flexure-Shear zone	Flexure zone		
4	A45T5C1	√	√	x	√	√
5		√	x	√	√	√
6		√	x	√	√	√
19	A50T5C1	√	√	x	√	√
20		√	x	√	√	√
21		√	x	√	√	√

Figure 4.6 : Specimen No.4 under four point bending with LVDT's at marked location

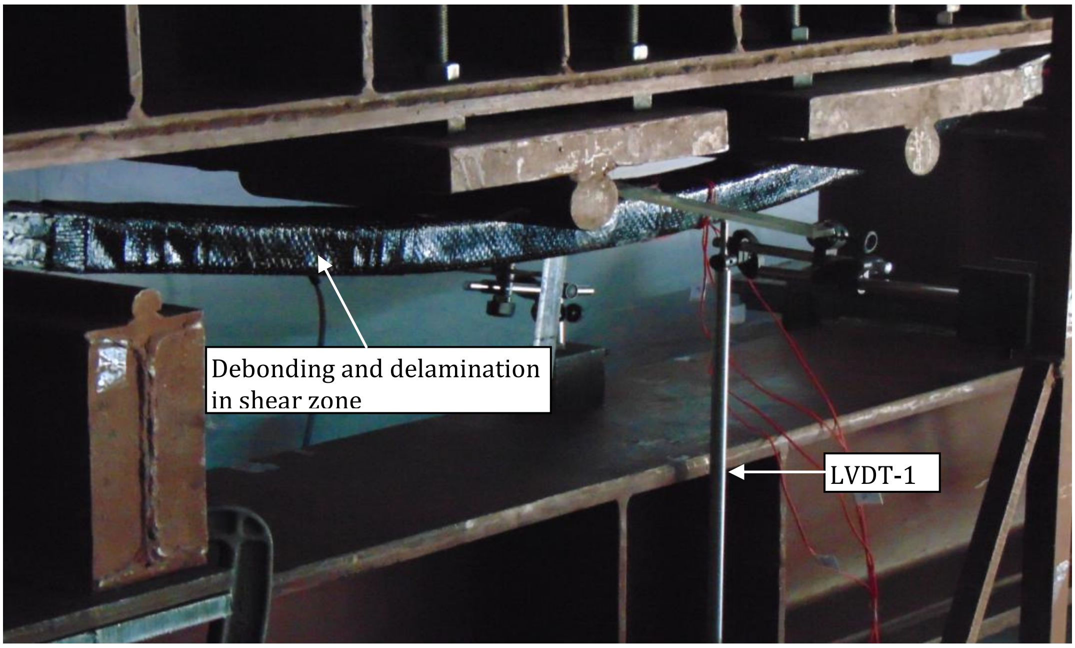


Figure 4.7 : Specimen No.4, debonding and delamination in shear zone

Figure 4.8 : Specimen No.4, debonding and delamination in shear zone (enlarged view)

Figures from Set-B are as below;

Figure 4.9 : Specimen No.19 under four point bending

Figure : Delamination and debonding in flexure-shear zone

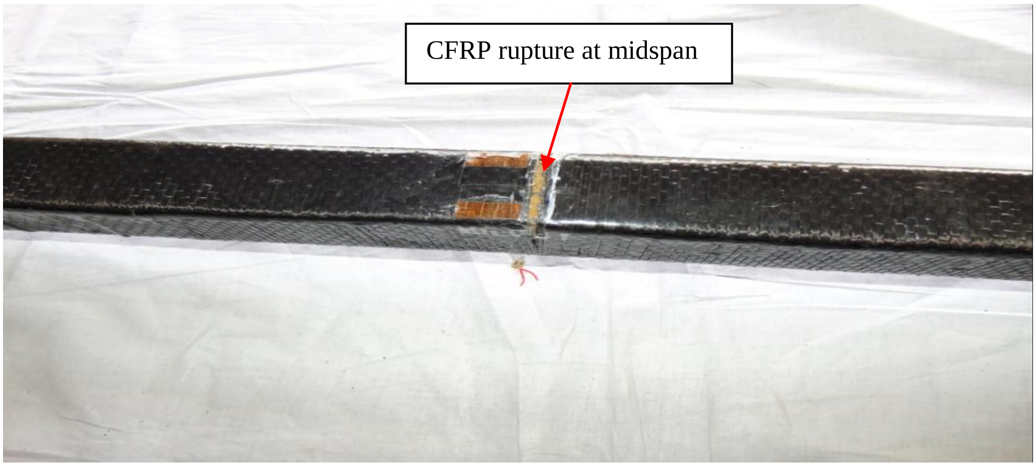

CFRP rupture at midspan

Figure 4.10 : Specimen No. 19, clear visible CFRP rupture on tension face

4.2.4 Strengthened Specimen Subset-3 (A45T5C2 and A50T5C2)

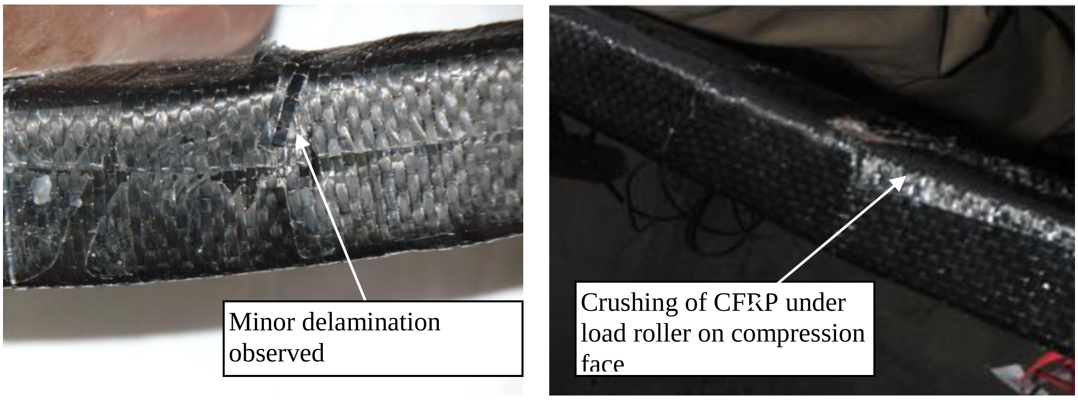
The failure of specimens tested in this subset was significantly different from those tested in Subset 2. Although there was no visible debonding between steel and adhesive, a cracking sound was observed during testing indicating that a possible debonding between the inner layers of CFRP (debonding noise at live testing observed), CFRP delamination and rupture observed. Crushing of CFRP layers under the load points were observed as shown in Fig 4.14. In addition, slight debonding can be observed on the outer hoop layer in the flexure zone. The observed failure modes for subset set are shown in a tabular form in Table 4.3. Figures 4.12 to 4.16 indicate that the CFRP layers are intact (no strengthening material failure was observed) after the testing was completed. The results from subsets 3, 4 and 5 indicate that the CFRP wrapping on top of internal formwork (card board) can transform the behavior of a steel angle from open to a closed section. This leads to change in failure from a combined FY and LTB to the preferred failure in flexure alone.

Table 4.3: Failure modes observed for subset-3

Specimen No.	Code	Steel and adhesive interface debonding	Adjacent CFRP interface debonding in		CFRP delamination	CFRP rupture
			Flexure-Shear zone	Flexure zone		
7	A45T5C2	√	x	√	x	√
8		√	x	√	x	√
9		√	x	√	x	√
22	A50T5C2	√	x	√	x	√
23		√	x	√	x	√
24		√	x	√	x	√

Figure 4.11: Intact CFRP wrapped specimen no. 7 before loading

Figure 4.12: No visible deboning or delamination on adjacent CFRP interface

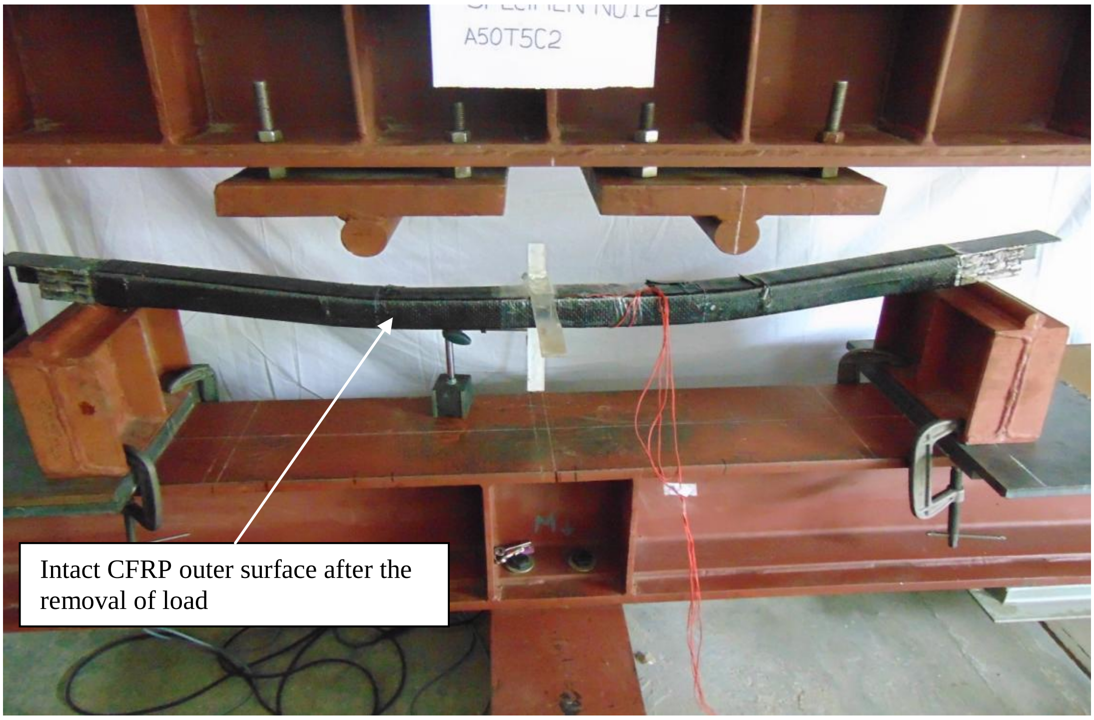


Minor delamination observed

Crushing of CFRP under load roller on compression face

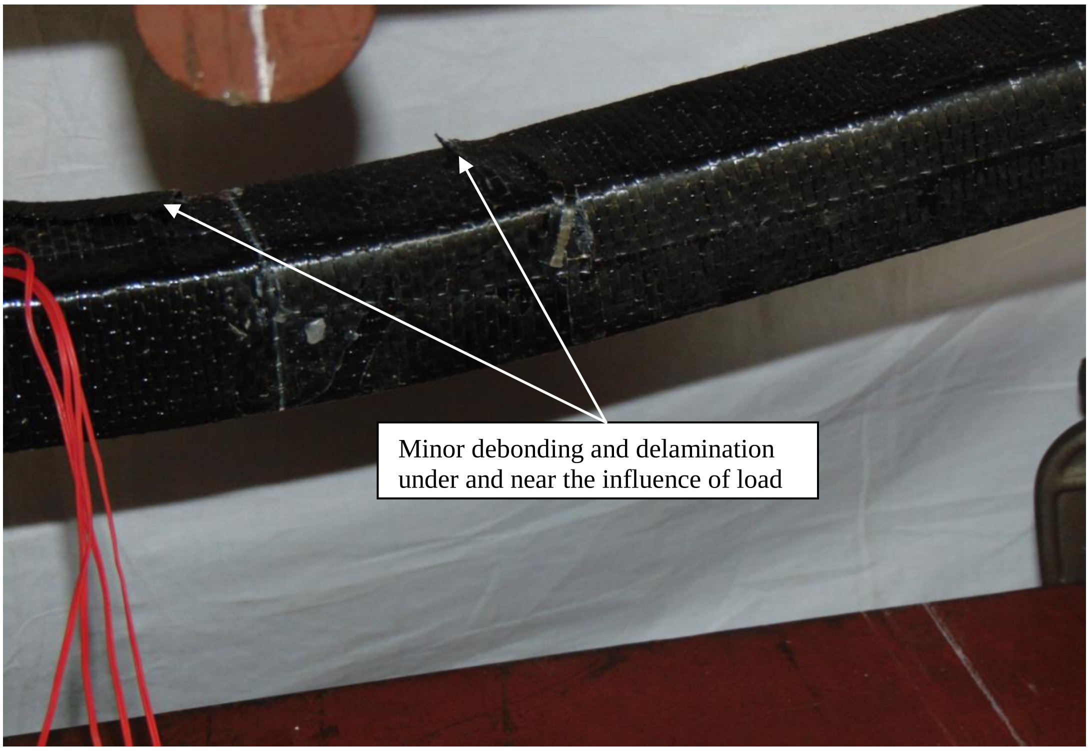
Figure 4.13: Specimen no. 7 delamination and CFRP crushing

Figures 4.15 and 4.16 are from set-B, subset-3.



Intact CFRP outer surface after the removal of load

Figure 4.14: Intact CFRP surface after removal of loading



Minor debonding and delamination under and near the influence of load

Figure 4.15: Minor delamination and debonding load rollers

4.2.5 Strengthened specimen subset-4 (A45T5CR and A50T5CR)

In this subset, the external bonding of CFRP typically used to reinforced concrete sections and closed structural steel sections was adopted for steel angle section for comparison purposes. Here the specimen was reinforced at the inside face of the angle (see Fig. 4.17), since the objective is to strengthen the tensile face of the section. It was observed that the specimen failed due to combination of debonding at the steel and CFRP interface, steel and adhesive, CFRP delamination and CFRP rupture. Since the bonding of CFRP to the angle section does not adequately change the moment of inertia, very little improvement in load carrying capacity was observed. Table 4.4, details the failure modes observed. Figures 4.18 to 4.20 indicate the failure modes observed:

Table 4.4: Failure modes observed for subset-4

Specimen No.	Code	Steel and adhesive interface debonding	CFRP delamination	CFRP rupture
10	A45T5CR	√	√	√
11		√	√	√
12		√	√	√
25	A50T5CR	√	√	√
26		√	√	√
27		√	√	√

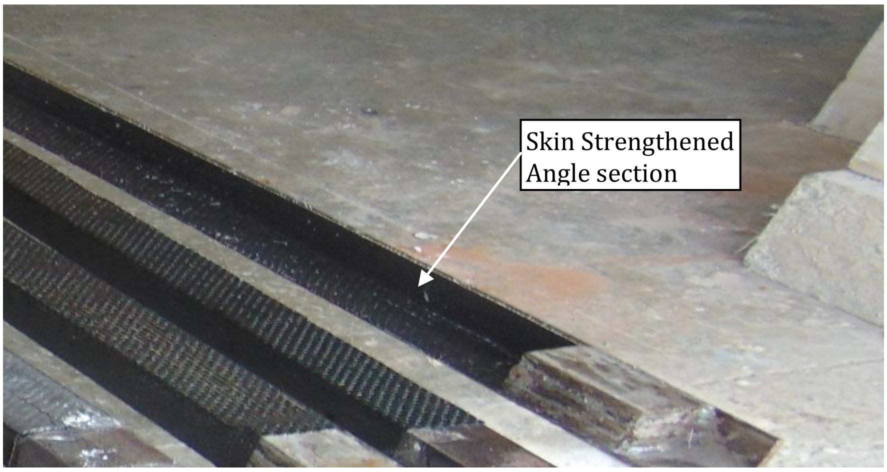


Figure 4.16: Skin Strengthened Angle section [0]

Figure 4.17: Specimen No. 25 under four point bending test setup

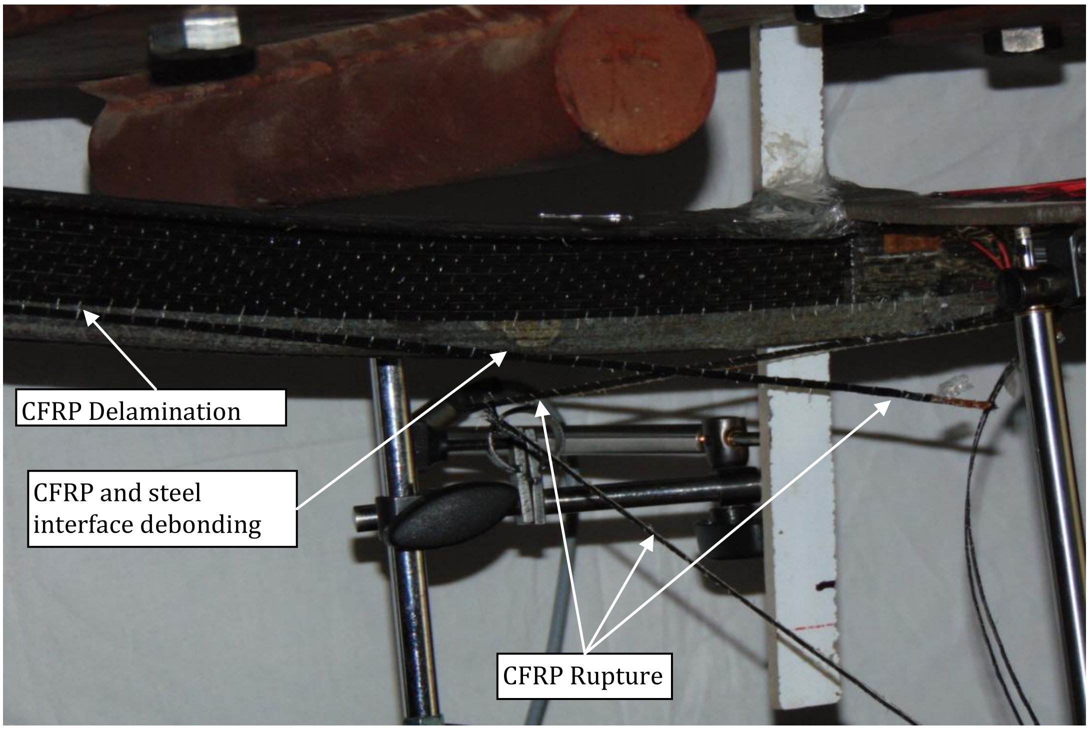


Figure 4.18: Typical failure pattern observed for subset-4

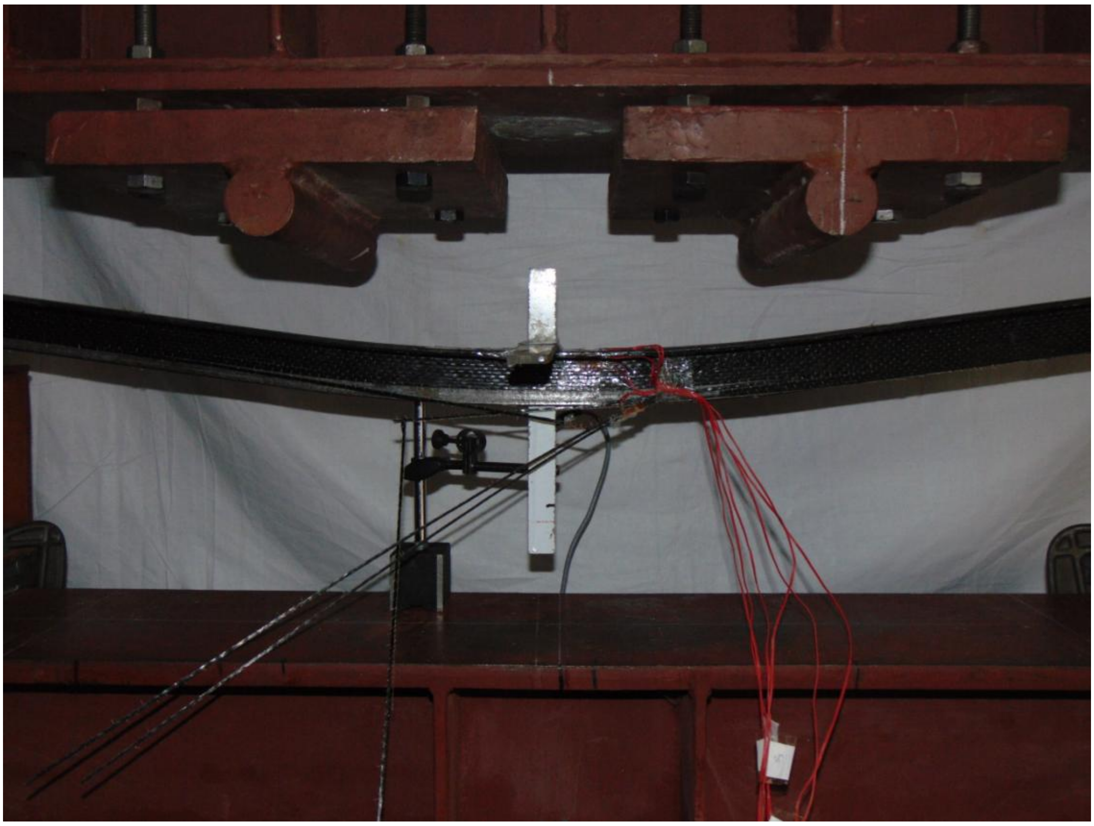


Figure 4.19: Specimen no. 10 after removal of loading

4.2.6 Strengthened Specimen Subset-5 (A45T5C0 and A50T5C0)

In this subset, the steel angle section was placed with an internal form work (card board) and one layer of CFRP layer wrapped around it such that the orientation of the fibers were along the length of the beam (unidirectional). It was observed that the failure of the specimen initiated due to combination of debonding at the steel and CFRP interface (steel side) and delamination of CFRP layers (card board side). This was later followed by CFRP rupture at the bottom card board side. Fig. 4.20 shows the above discussed failure modes for subset 5. The results indicate that there was very little increase in load carrying capacity compared to control specimens due to the fact that the unidirectional CFRP layers were not adequately braced in the lateral direction to ensure that the fibers remained straight and carried the load. During testing, the card board fibers started to dilate (expand) leading to dislocation of unidirectional CFRP fibers and therefore a reduction in ultimate load. Table 4.5, provides details of failure modes observed. Figures 4.21 to 4.23 shows the failure modes observed during and after the testing.

Table 4.5: Failure modes observed for subset-5

Specimen No.	Code	Steel and adhesive interface debonding	CFRP delamination	CFRP rupture
13	A45T5C0	√	√	√
14		√	√	√
15		√	√	√
28	A50T5C0	√	√	√
29		√	√	√
30		√	√	√

Figure 4.20: Specimen no. 30 under four point bending test setup

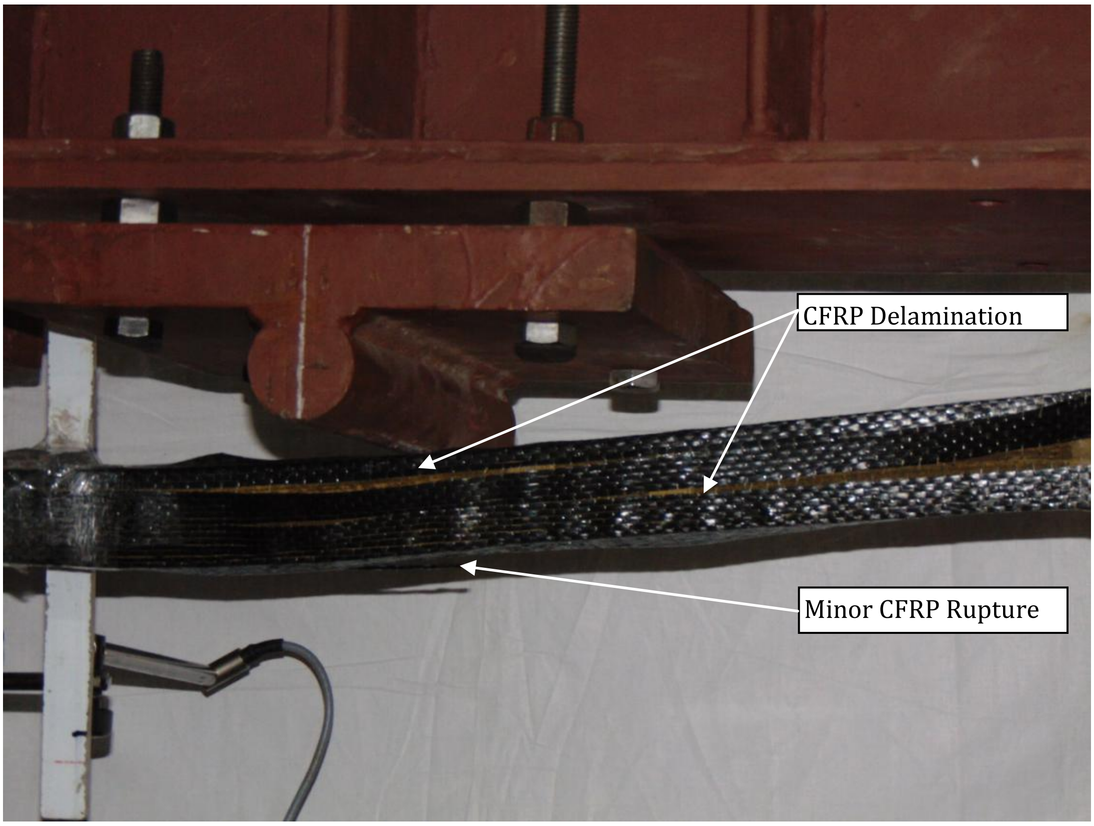


Figure 4.21: Delamination of CFRP on sides of wrapped beam.

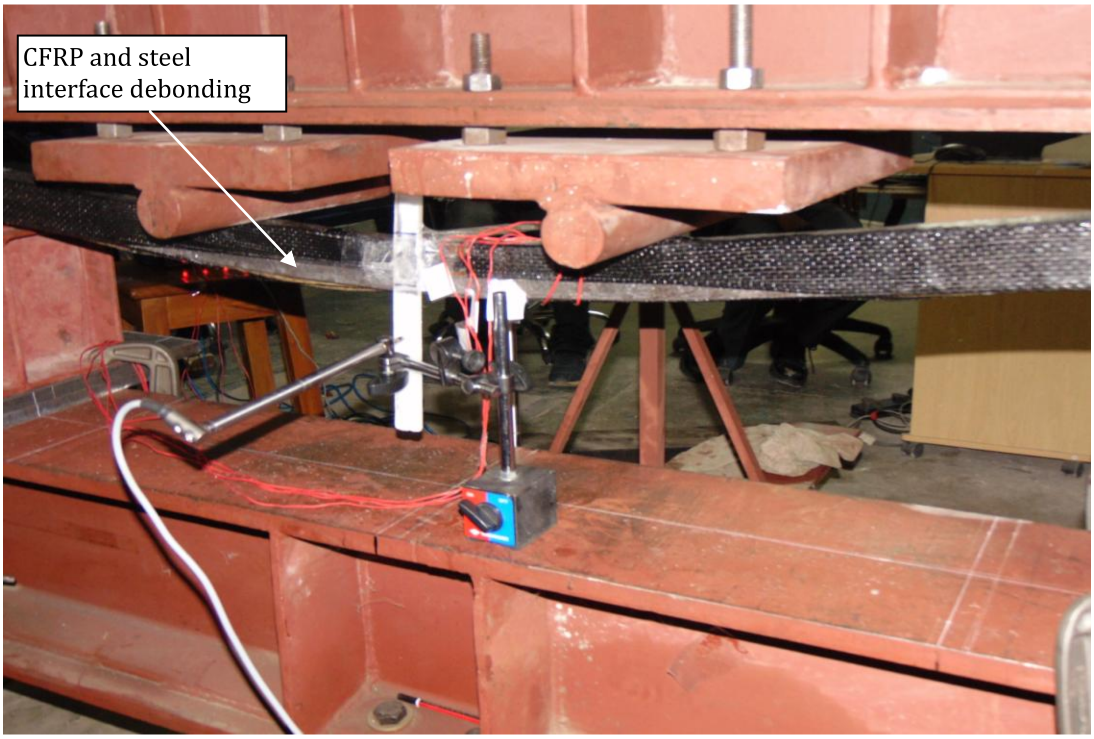


Figure 4.22: CFRP and steel interface debonding.

4.3 Load Vs Displacement Comparison

4.3.1 Control Specimen

- Set-A (Specimen Nos.1, 2 and 3)

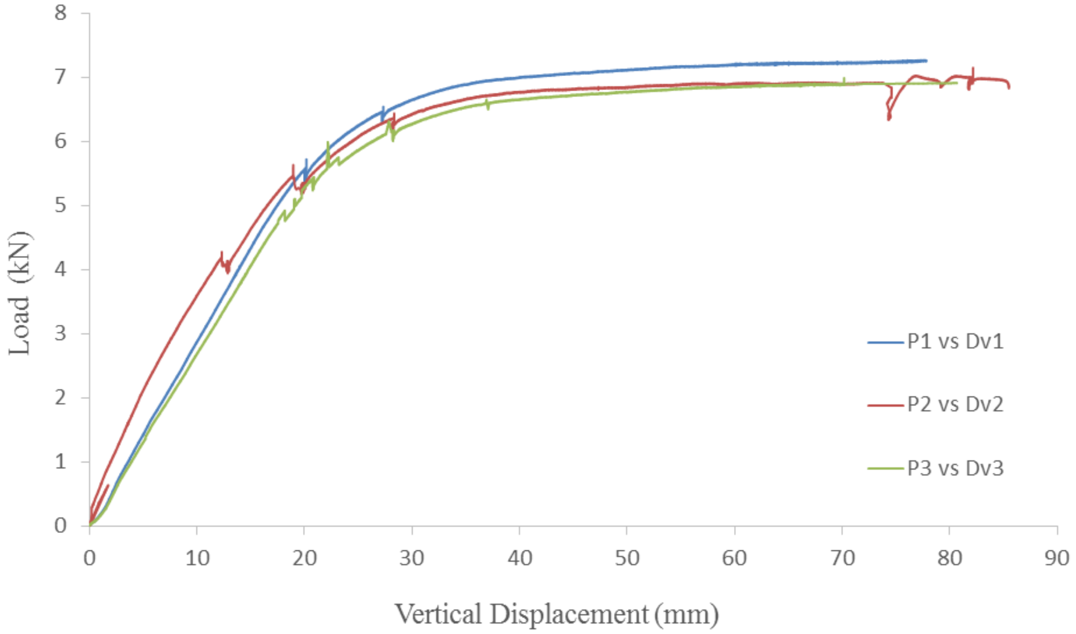


Figure 4.23: Set-A; Subset-1, Vertical load (P) vs Vertical Displacement (Dv)

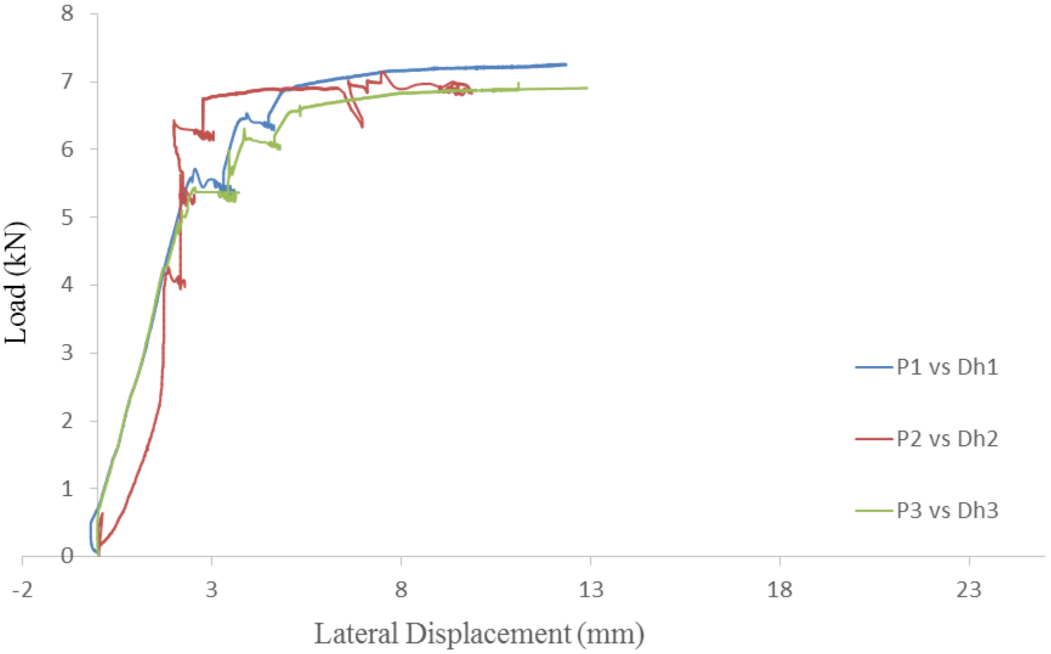


Figure 4.24: Set-A; Subset-1, Vertical load (P) vs Lateral Displacement (Dh)

Figure 4.24, shows the load vs mid-span vertical displacement for bare steel section (subset-1). These tests were taken as bench mark tests (control specimens) to study the effectiveness of various CFRP strengthening methods carried out in this present work. During testing it was observed that the specimen started to deflect vertically at the initial stages of loading followed by twisting and lateral displacement. The kinks in Fig. 4.24 indicate that there is a slight drop in load which may be due to adjustment of supports as they were not finished properly after welding of steel plates. It can be observed that the behavior of all the three control specimens follow a uniform load displacement trend. The variation in ultimate load was less than 10%. This variation may be due to distortion induced in the steel angle section due to welding of steel support plates during testing there was no lifting or lateral slip of specimen at supports was observed. Figure 4.25, shows the load vs lateral displacement at mid-span for control specimens.

- Set-B (Specimen Nos. 16, 17 and 18)

Figure 4.26, shows the similar behavior to the set-A. A close look at the graph shows uniformity among three. For specimen 17 after 70 mm of vertical displacement there is sudden increase in load for a small increase in displacement and again a sudden decrease observed due to locking up of perspex strip with tightening screw of magnetic stand for LVDT-1 (Setup shortcoming). Figure 4.27, shows there is back and forth movement for all three specimens and there is slight marginal non-uniformity among them

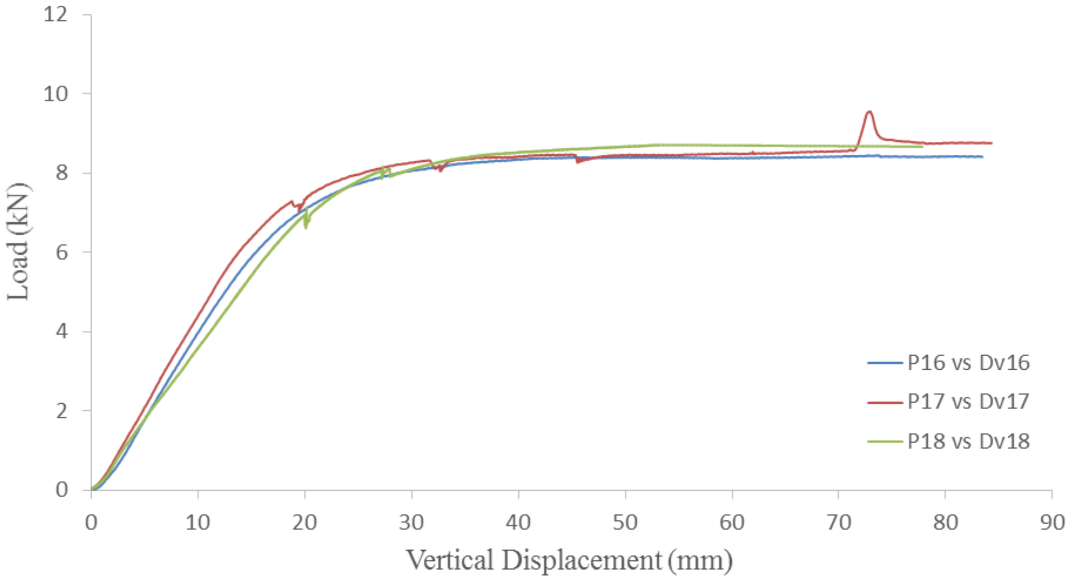


Figure 4.25: Set-B; Subset-1, Vertical load (P) vs Vertical Displacement (Dv)

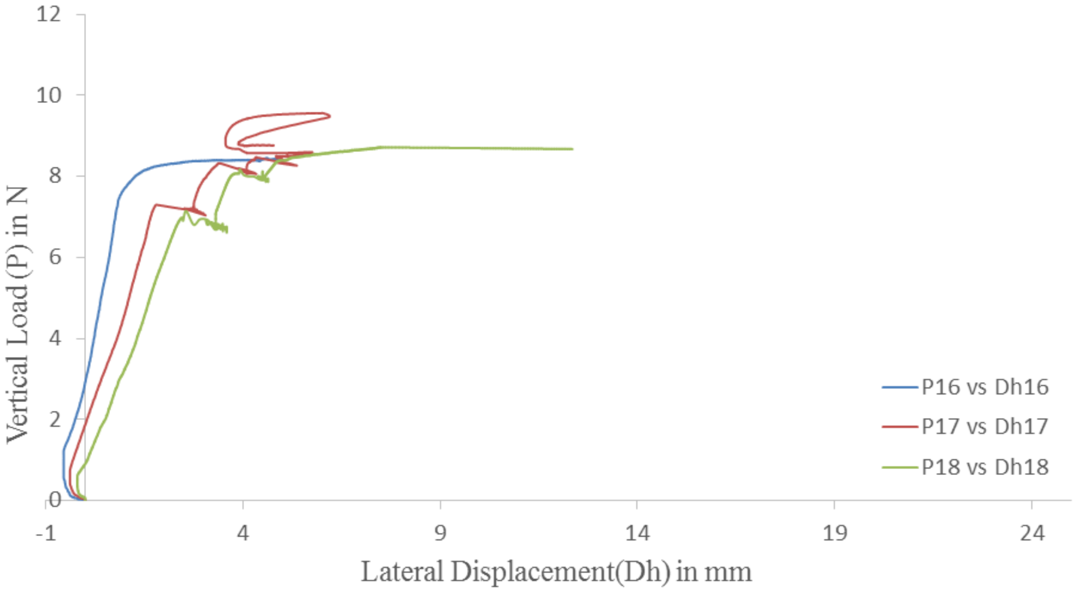


Figure 4.26: Set-B; Subset-1, Vertical load (P) vs Lateral Displacement (Dh)

4.3.2 Strengthened Specimens Subset-2 (A45T5C1 and A50T5C1)

- Set-A (Specimen Nos. 4, 5 and 6)

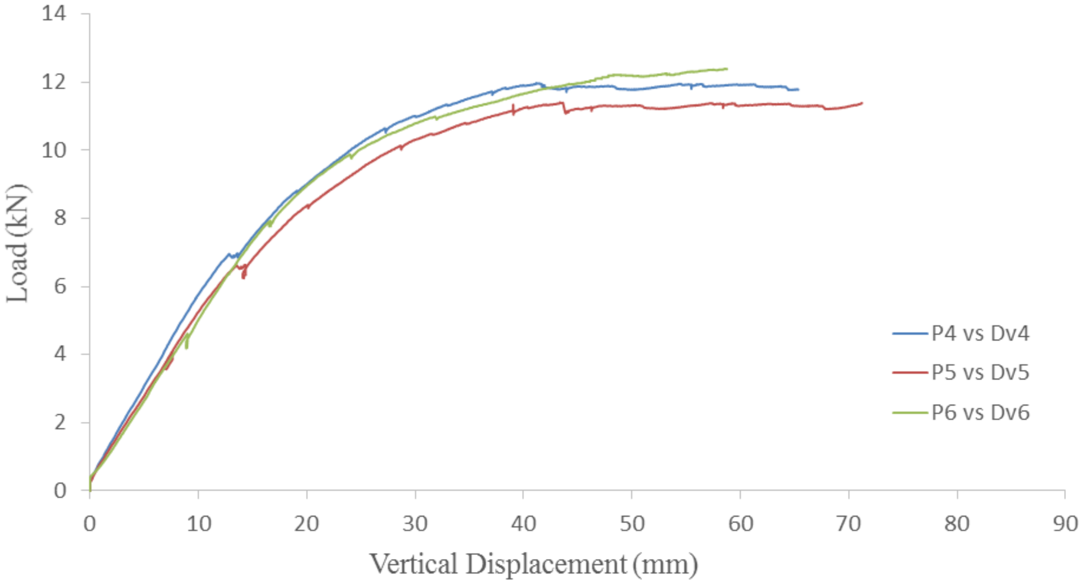


Figure 4.27: Set-A; Subset-2, Vertical load (P) vs Vertical Displacement (Dv)

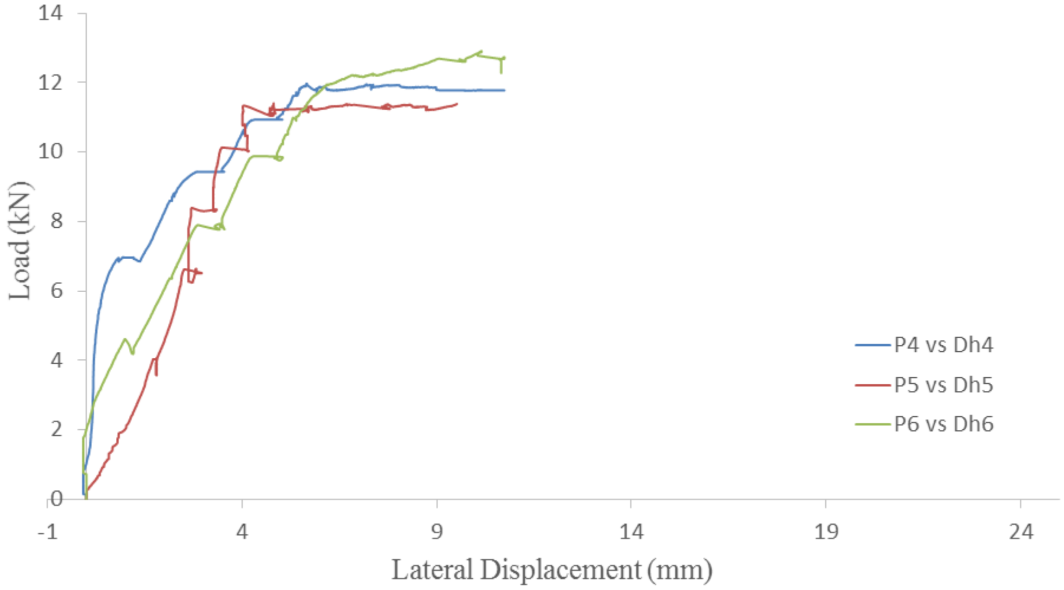


Figure 4.28: Set-A; Subset-2, Vertical load (P) vs Lateral Displacement (Dh)

Figure 4.28, shows vertical load (P) vs vertical displacement (Dv) for subset-2. There is uniformity (± 10 % variation) among three of the specimens. It shows initial holding up of the slope and then drop in load due to starting of debonding or rupture of CFRP at kinks. Increase in ultimate load Pu observed over previous subset. Figure 4.29, shows lateral behavior captured through the lateral LVDT-2. It shows initial holding up of load increase for approximately no increase in lateral displacement or for very small lateral displacement. It shows transformation of LTB into FY.

- Set-B (Specimen Nos. 19, 20 and 21)

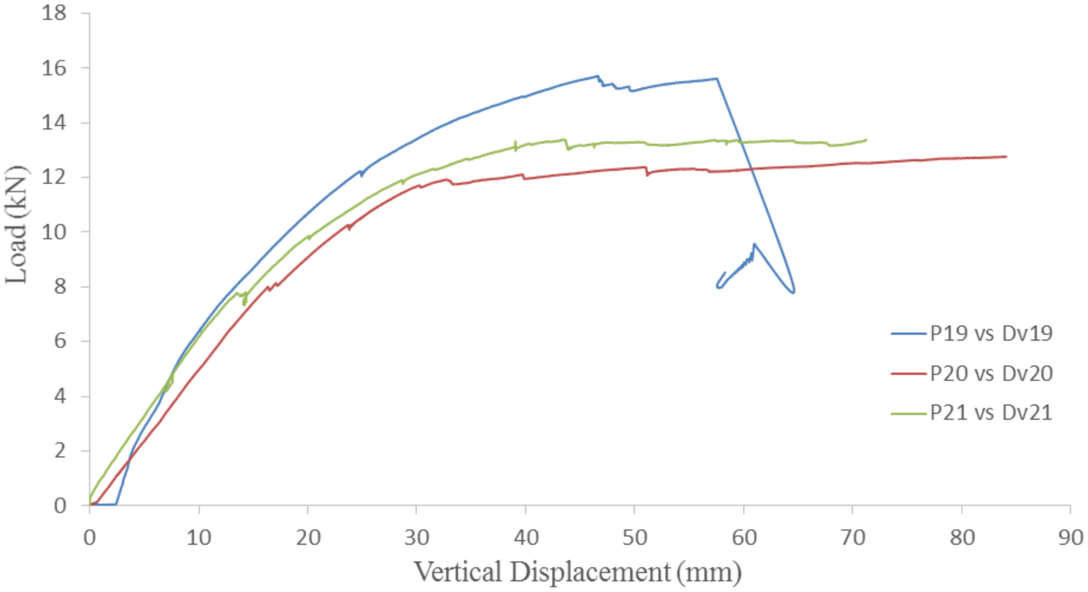


Figure 4.29: Set-B; Subset-2, Vertical load (P) vs Vertical Displacement (Dv)

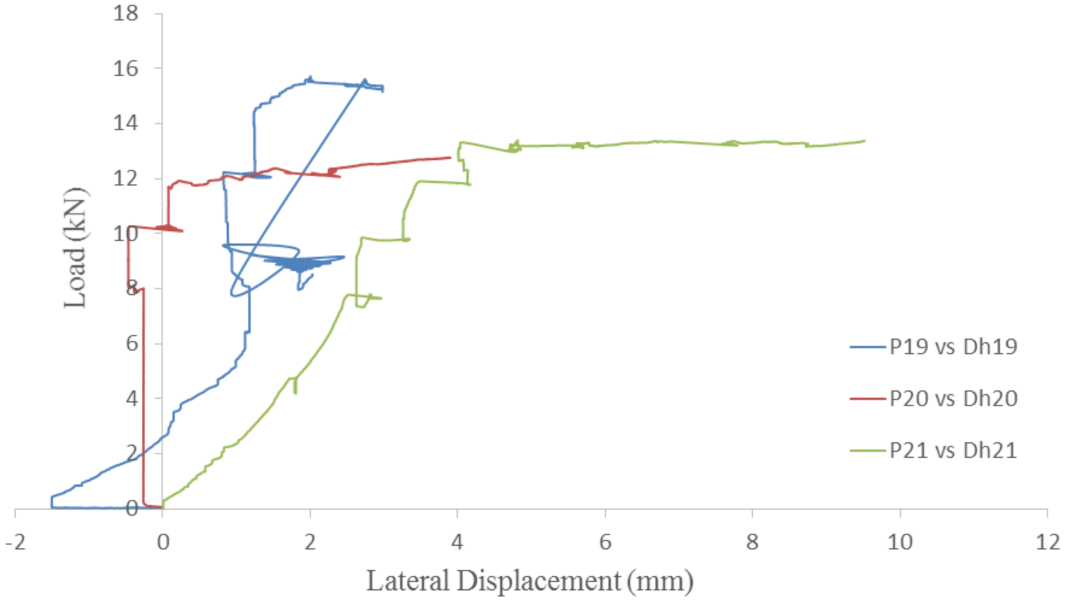


Figure 4.30: Set-B; Subset-2, Vertical load (P) vs Lateral Displacement (Dh)

Figure 4.31, shows vertical load (P) vs vertical displacement (Dv) for subset-2. Specimen 19 shows different initial behavior than other two specimens for range of 3 mm due to fabrication shortcomings (supports finishing and CFRP wrapping; less rolling). It can be seen for specimen 19 there is sudden drop in load carrying capacity after 57 mm vertical displacement up to the load carrying capacity of bare steel specimen, due to simultaneous debonding and rupture of CFRP. Other specimens 20 and 21 are showing agreement among themselves. It can be seen from fig. 4.30, for specimen 20 there is increase in vertical load for approximately no increase in lateral displacement. For other two specimen's effect of increase in vertical load for less increase in lateral displacement observed.

4.3.3 Strengthened Specimens Subset-3 (A45T5C2 and A50T5C2)

- Set-A (Specimen Nos. 7, 8 and 9)

From Fig. 4.32, it can be seen that there is a good marginal increase in load carrying capacity and agreement between specimen 7 and 9. Zigzag portion of graph for specimen 8 is due to slight debonding or delamination of CFRP from parent material steel. A close look at graph for specimen 9 shows that after rupture of extreme longitudinal CFRP at 59 mm there is gradual drop in load up to the load carrying capacity of previous subset-2 and again holding up the trend of carrying the load further for approximately 18 mm. For this subset fewer kinks observed due to intact CFRP wrapping and quality control measures. Figure 4.33, Shows an increase of load for less or no increase in lateral displacement. The load drop steps and increase in displacement are due to various CFRP failure modes except rupture of CFRP. LVDT -2 readings for specimen -7 were off due to slip of LVDT pointer from the supporting stand and same recorded results are presented.

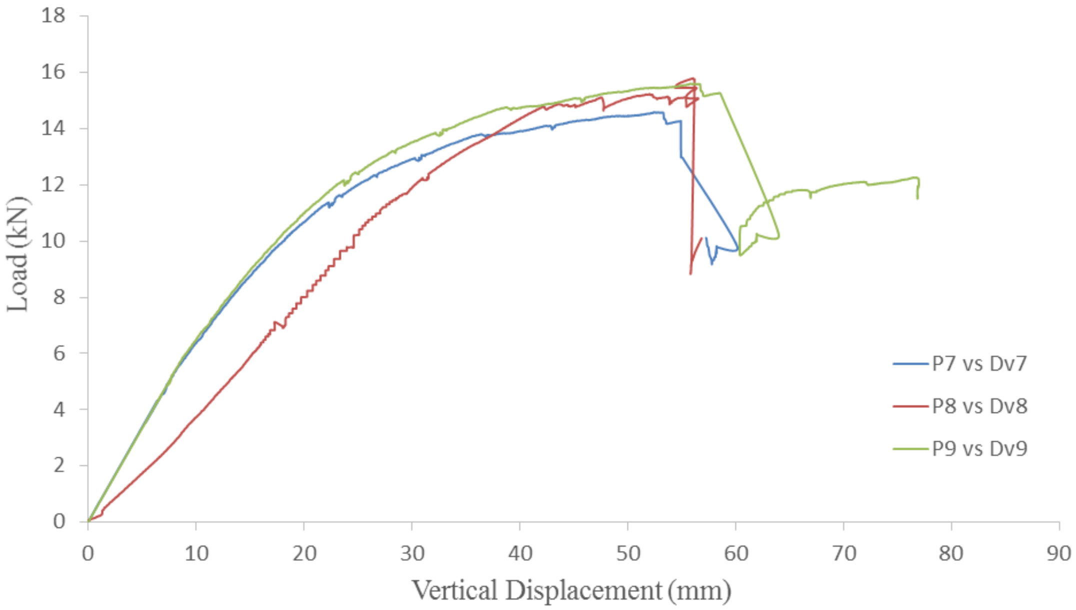


Figure 4.31: Set-A; Subset-3, Vertical load (P) vs Vertical Displacement (Dv)

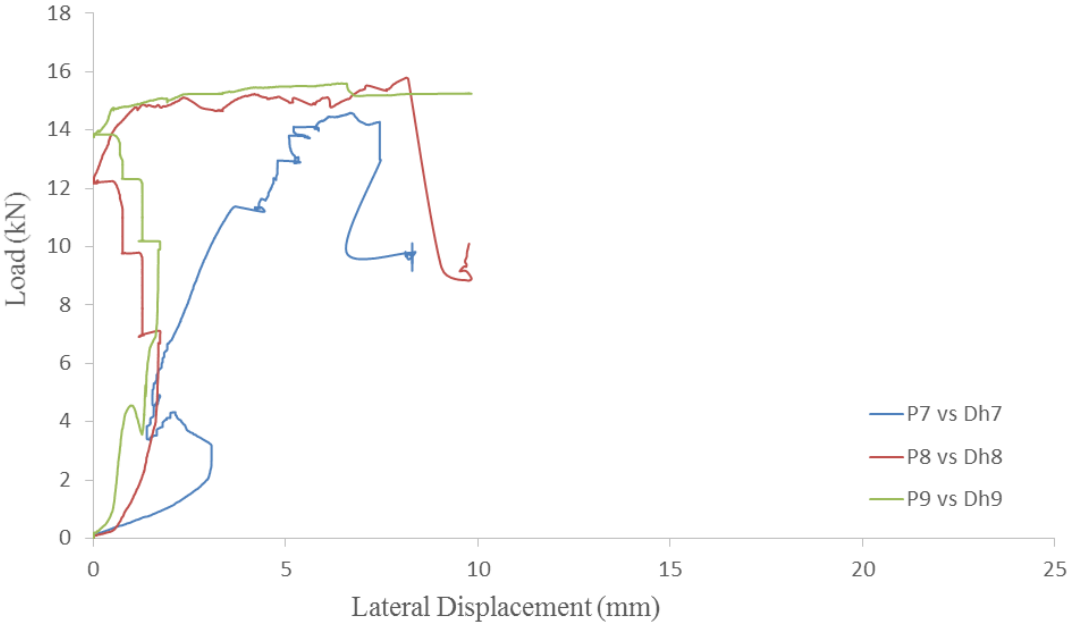


Figure 4.32: Set-A; Subset-3, Vertical load (P) vs Lateral Displacement (Dh)

- Set-B (Specimen Nos. 22, 23 and 24)

For this subset, it can be seen from fig. 4.34, for specimens 22 and 23, local debonding of CFRP from steel interface or bond failure causing the drop in load at some intervals of increase in vertical displacement. From fig. 4.35, it can be seen that there is increase in load for less increase in lateral displacement as the change in section from open to closed, is resisting the twist. For specimen no. 23 there is initial lateral movement but after 1.4 mm it has resisted the LTB in same manner alike other two specimens. Readings of specimen no. 22 are off as it was blocked in between the test to the tightening screw of magnetic stand.

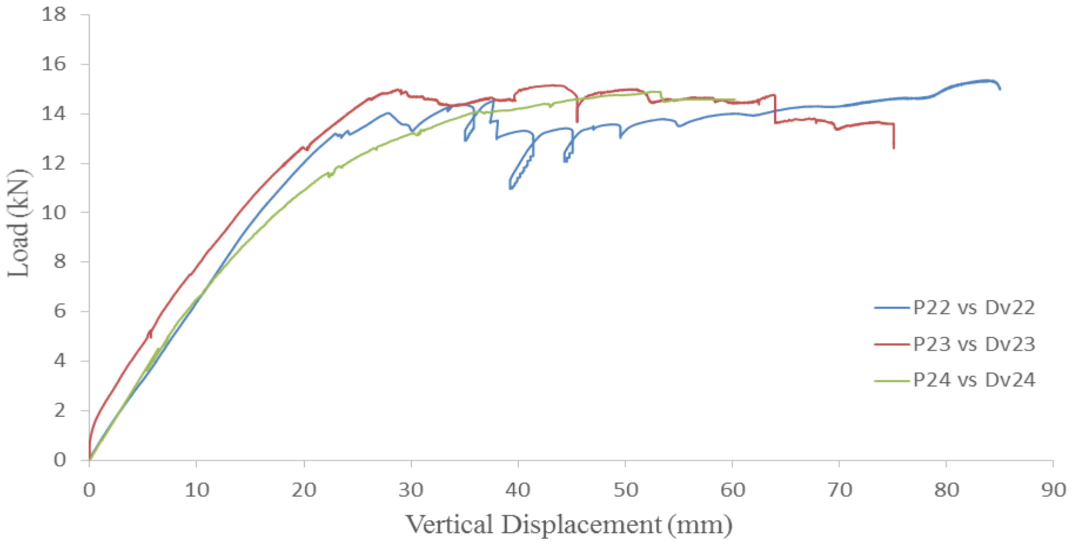


Figure 4.33: Set-B; Subset-3, Vertical load (P) vs Vertical Displacement (Dv)

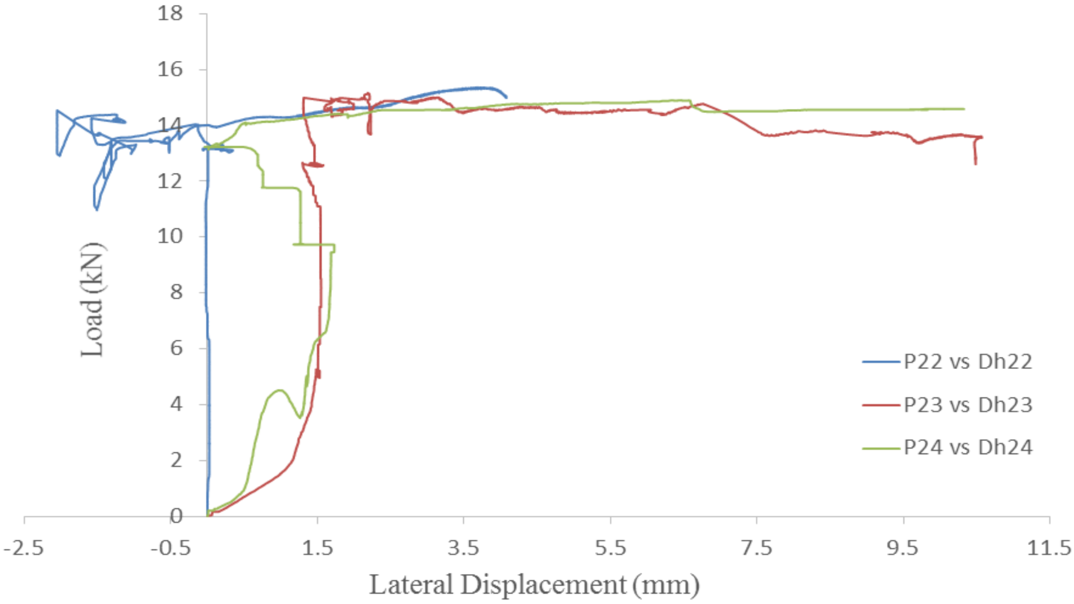


Figure 4.34: Set-B; Subset-3, Vertical load (P) vs Lateral Displacement (Dh)

4.3.4 Strengthened specimen subset-4 (A45T5CR and A50T5CR)

- Set-A (Specimen Nos. 10, 11 and 12)
-

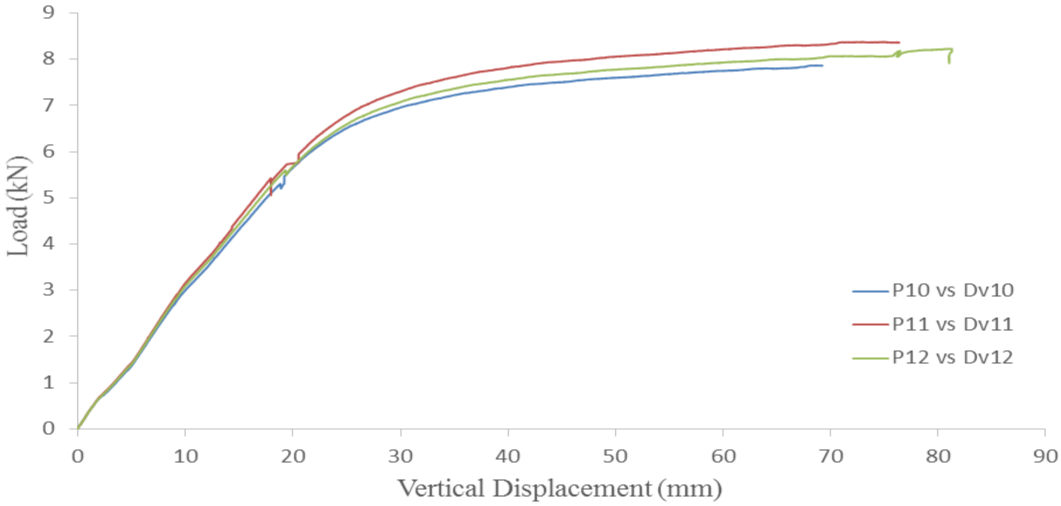


Figure 4.35: Set-A; Subset-4, Vertical load (P) vs Vertical Displacement (Dv)

Figure 4.36, shows P vs Dv behavior for externally bonded CFRP specimens. All three specimens are having uniform behavior (±10% variation). Kinks in the graph indicate the LTB behavior simultaneously with FY. At the time of test for specimens 10 and 11 LVDT -1 got strucked with tightening screw so the failure mode could not be recorded. The drop at the tip for specimen 12's indicates initiation of failure due to debonding.

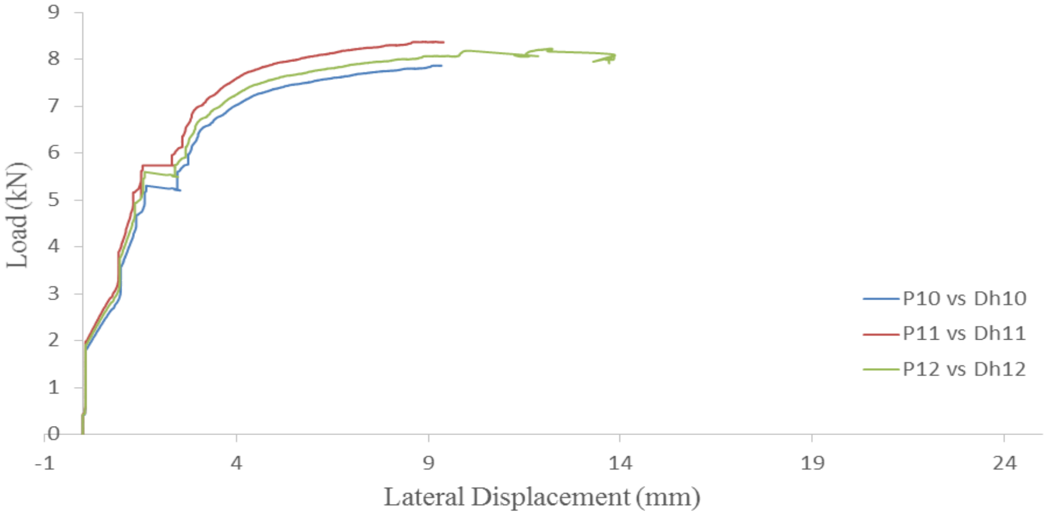


Figure 4.36: Set-B; Subset-4, Vertical load (P) vs Lateral Displacement (Dh)

Figure 4.37, variation load vs lateral displacement. All specimens are showing uniformity of behavior up to certain load and then there is change in the slopes due to failure of bond as observed during testing.

- Set-B (Specimen Nos. 25, 26 and 27)

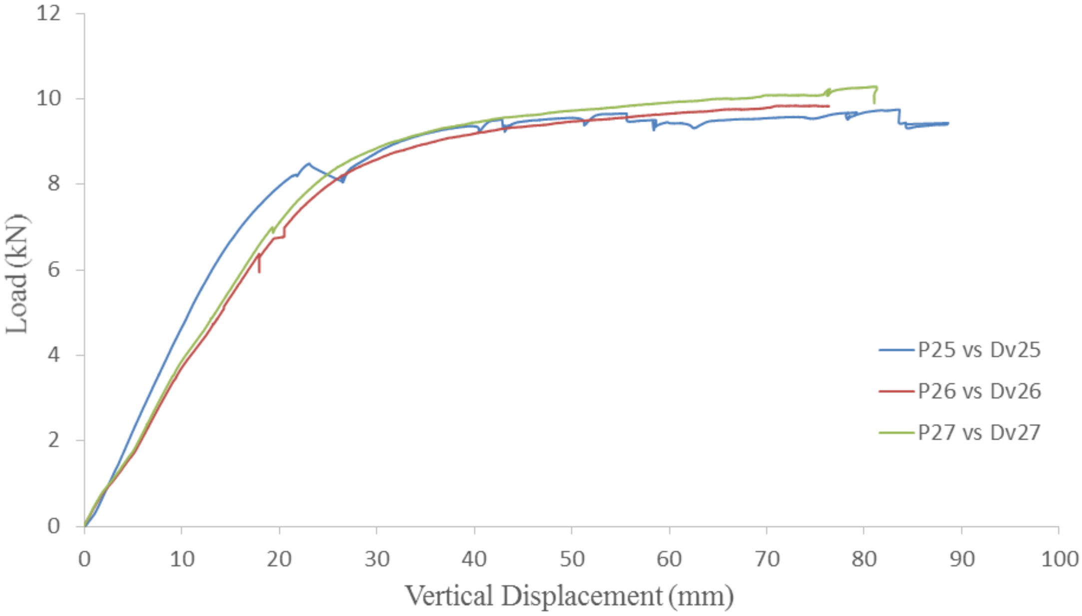


Figure 4.37: Set-B; Subset-4, Vertical load (P) vs Vertical Displacement (Dv)

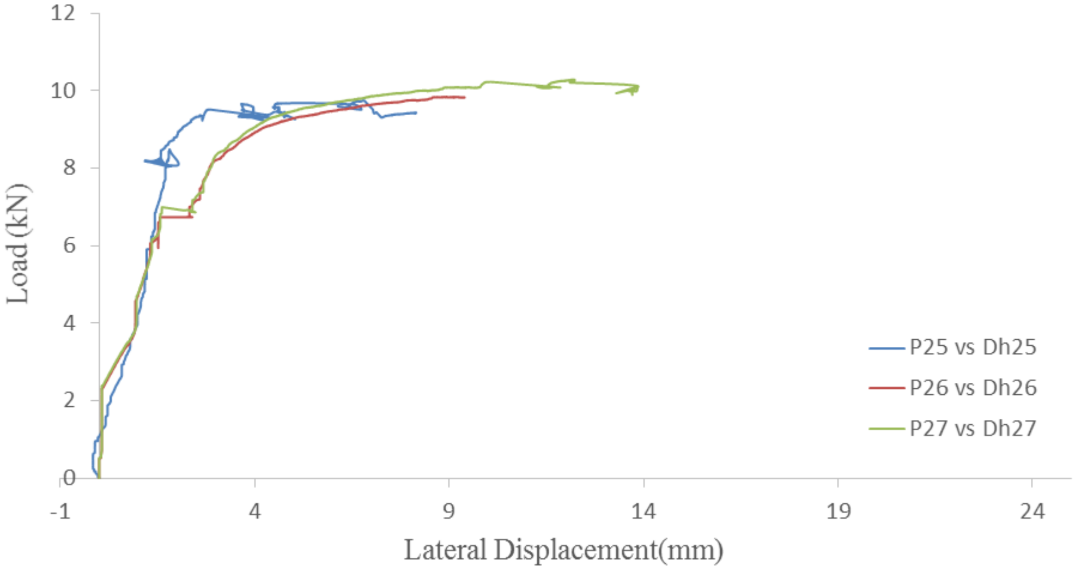


Figure 4.38: Set-B; Subset-4, Vertical load (P) vs Lateral Displacement (Dh)

Figure 4.38, indicates more kinks than previous subset of same strengthening configuration. For specimen 25 clear rupture of CFRP was seen and it is evident in the graph also. Behavior for specimens 26 and 27 is uniform (±5% variation).

Figure 4.39, indicates initial load increase for no or less increase in lateral displacement. Specimens tried to resist the LTB but could not hold it up for long or for large lateral displacement. Kinks are clear indication of CFRP rupture in tension zone.

4.3.5 Strengthened Specimen Subset-5 (A45T5C0 and A50T5C0)

- Set-A (Specimen Nos. 13, 14 and 15)

Figure 4.40, shows a close uniformity among the graphs for all the specimens. More kinks shows simultaneous debonding and delamination failure. Dropping of load carrying capacity to capacity of control specimens can be observed. Figure 4.41, shows linear increase in the lateral displacement of all three specimens with approximately no improvement in resistance to LTB.

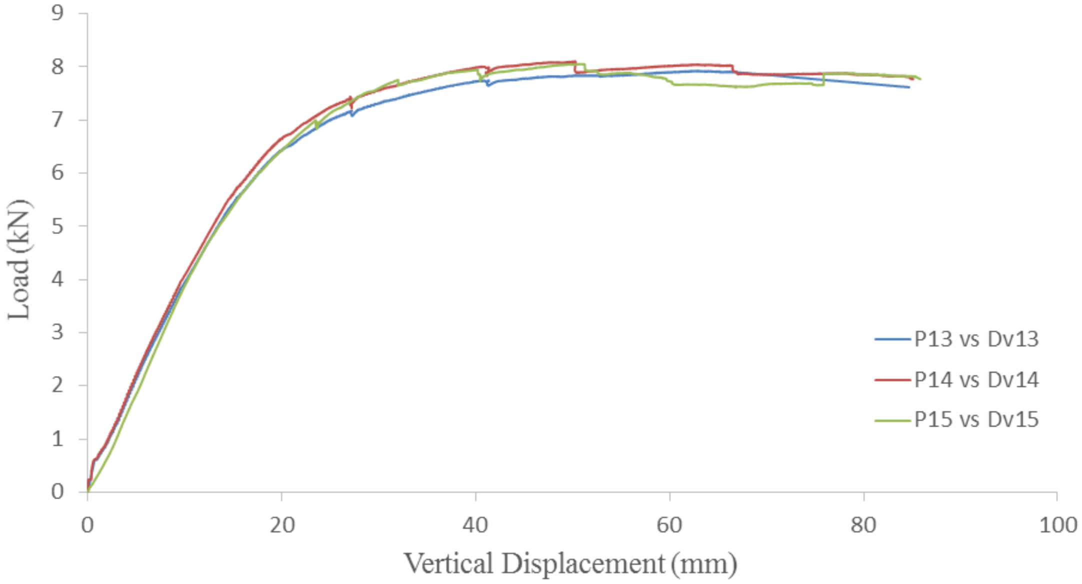


Figure 4.39: Set-A; Subset-5, Vertical load (P) vs Vertical Displacement (Dv)

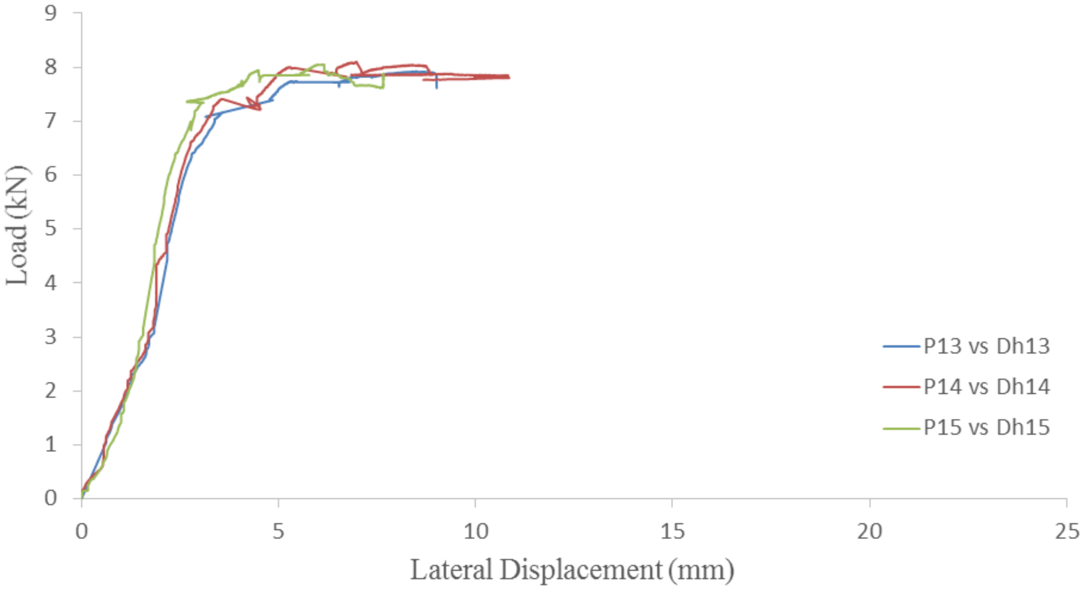


Figure 4.40: Set-A; Subset-5, Vertical load (P) vs Lateral Displacement (Dh)

- Set-B (Specimen Nos. 28, 29 and 30)

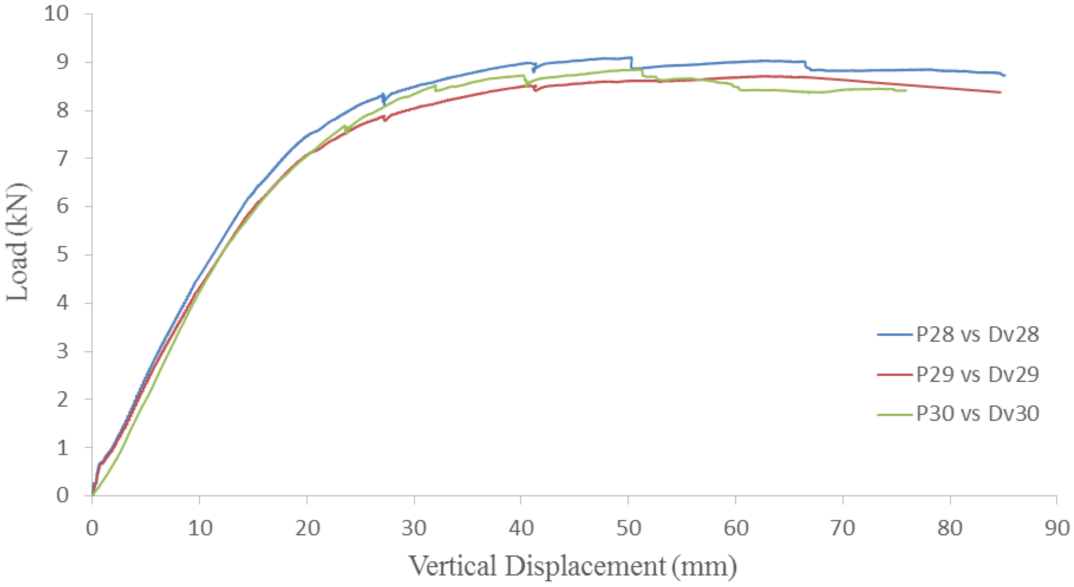


Figure 4.41: Set-B; Subset-5, Vertical load (P) vs Vertical Displacement (Dv)

Figure 4.42, shows uniformity among three specimens (±5% variation). The sudden load drops indicate the failure of CFRP due to debonding and delamination.

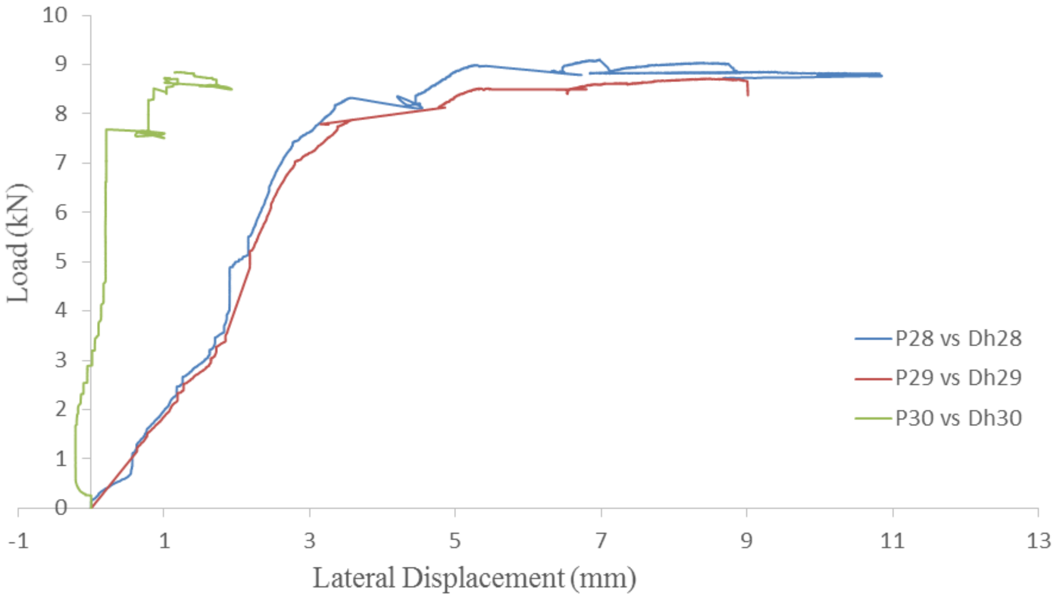


Figure 4.42: Set-B; Subset-5, Vertical load (P) vs Lateral Displacement (Dh)

Figure 4.43, shows uniformity of results for specimens 28 and 29 as for specimen 30, readings were off. There is linear increase in load with lateral displacement with less kinks. It indicates less resistance to LTB for this subset.

4.3.6 Comparison of subsets

- Set-A

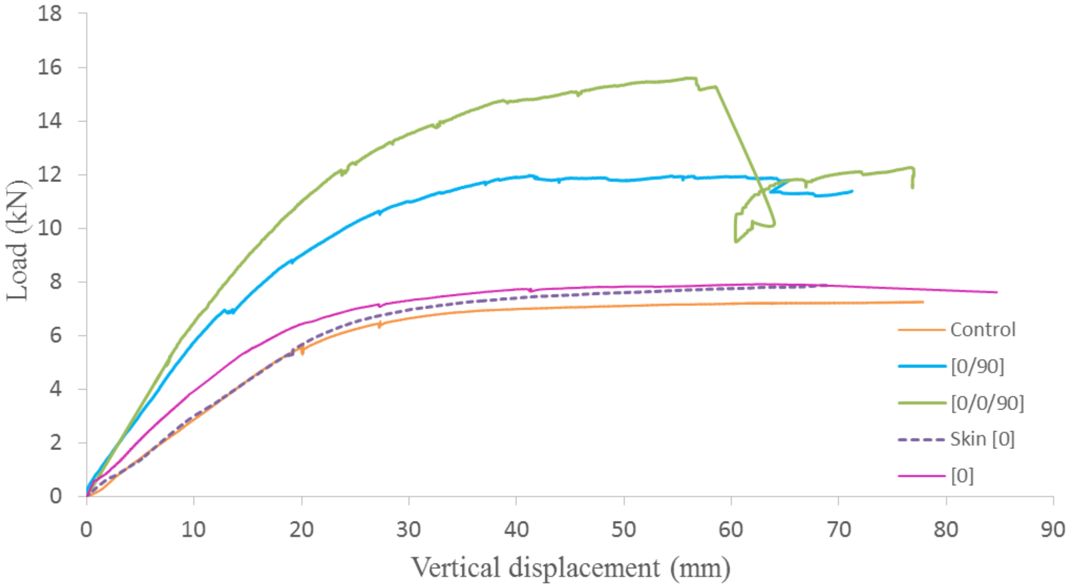


Figure 4.43: Set-A; Vertical load (P) vs Vertical Displacement (Dv)

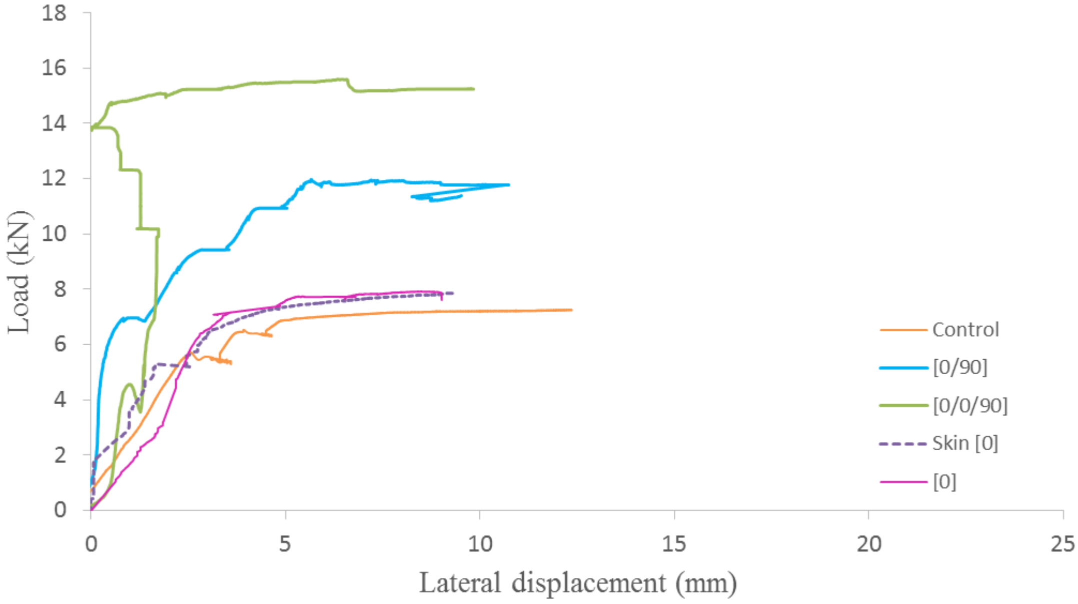


Figure 4.44: Set-A; Vertical load (P) vs Lateral Displacement (Dh)

The effectiveness of different strengthening configurations carried out in the present work is compared with the control specimen (bare steel section) to quantify the percentage increase in stiffness and ultimate load carrying capacity as shown in Figs. 4.44 and 4.45. It can be observed that there is an insignificant increase in stiffness and strength when the steel angle section is initially skin strengthened with by unidirectional (0^0). This may be due to the fact that there is not an adequate increase in the bending stiffness (EI) since the moment of inertia due to the application of CFRP in the skin strengthened configuration is considerably less. The next three strengthening approaches used an internal form work in the form of card board attached to the angle section and the CFRP was wrapped around it. This essentially transformed the open section to a closed section configuration thereby significantly increasing the bending stiffness due to the increase in moment of inertia. The first step in this closed section configuration approach was to wrap one layer of unidirectional (0^0) CFRP around the steel and the card board (internal form work). It can be observed from Figs 4.44 and 4.45 that there is a slight increase in stiffness whereas the ultimate load capacity remained similar to the control and skin strengthened specimen. This behavior is expected since the absence of any reinforcement in the hoop direction will not ensure that the unidirectional layers will stay in their original position and tend to deviate due to the twisting of the specimen at midspan due to unsymmetrical bending.

The other two configurations in the closed section were wrapping of CFRP in ($0^0/90^0$) and ($0^0/0^0/90^0$). It can be observed that there is a significant increase in strength and stiffness due to the addition of a hoop layer (90^0) which confines the unidirectional layers and ensuring that the closed section shape remains intact. In addition, the unidirectional layers have a tendency to buckle locally if adequate brace is not provided. The presence of hoop layer inherently braces (unbraced length is zero) the unidirectional layers ensuring no micro buckling or kinking takes place thereby extracting maximum strength and stiffness from unidirectional layers. Figs 4.44 and 4.45 indicate that strength increased by 76% compared to control steel specimen.

The significant improvement in load carrying capacity can be seen from fig. no. It can be seen that for subset-3 (A45TC2- $0^0/0^0/90^0$), onset of (0^0) extreme CFRP wrap rupture and then drop in load carrying capacity linearly upto load carrying capacity of subset-2 (A45T5C1- $0^0/90^0$). It is evident from this it has not only increased the load carrying capacity but also the stiffness of the system. This is mainly due to the transformation of failure mode from [FY+LTB] for control specimens (open sections] into [FY] upto extent. CFRP wrap has shown enhanced ductility and upto certain extent an increase in toughness with increase in load for reference vertical displacement in comparison with all other methods. Specifically it can be seen there is little increment in load carrying capacity for subset-4 (A45T5CR) and subset-5 (A45T5C0) in comparison with reference control specimen subset-1. It is mainly due to subset-4 (A45T5CR)'s less resistance to failure mode [FY+LTB] as section shape configuration remained unchanged. For subset-5 (A45T5C0), due to absence of hoop wrap there is slight increase in the load carrying capacity in comparison with control specimen as well as subset-4, as the section transformed from open section to closed section.

Load vs vertical displacement for subset-3 (A45TC2- $0^0/0^0/90^0$) and subset-2 (A45T5C1- $0^0/90^0$) provides the measure of stiffening effect in elastic region over control specimens and subsets 4 and 5. Also it provides significant gain of strength and stiffness in post yield zone. This is an important consideration specifically for bridge application where live load deflection limits are very stringent. But in contrast to that it can be seen that for subset-4 and 5, there is no or little stiffening effect in comparison to control specimens in elastic region as well as post yield region. The stiffening effect is mainly due to higher elastic modulus high tensile strength of CFRP than the structural steel and quality control at the time of wrapping of CFRP [(A45TC2- $0^0/0^0/90^0$) and (A45T5C1- $0^0/90^0$)] .

The results from Fig. 4.44, load vs lateral displacement for subset-3 (A45TC2- $0^0/0^0/90^0$) and subset-2 (A45TC1- $0^0/90^0$) indicate improved resistance to [LTB] in elastic region over all other methods. Subset-1, 4 and 5 have followed approximately same trend except for subset-4 which has more resistance to [LTB] over other subsets-5.

- Set-B

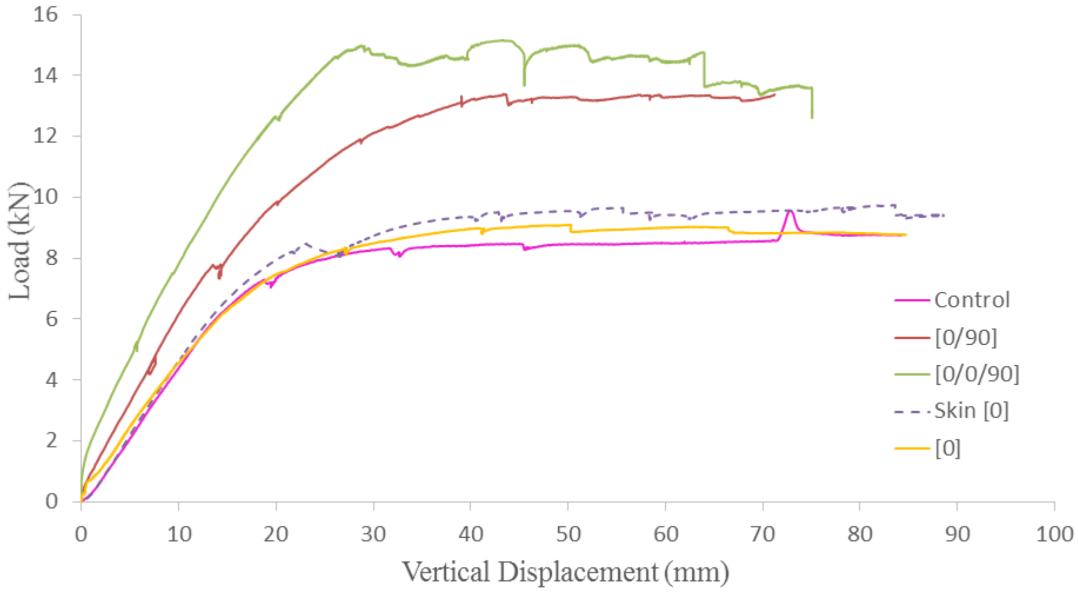


Figure 4.45: Set-B; Vertical load (P) vs Vertical Displacement (Dv)

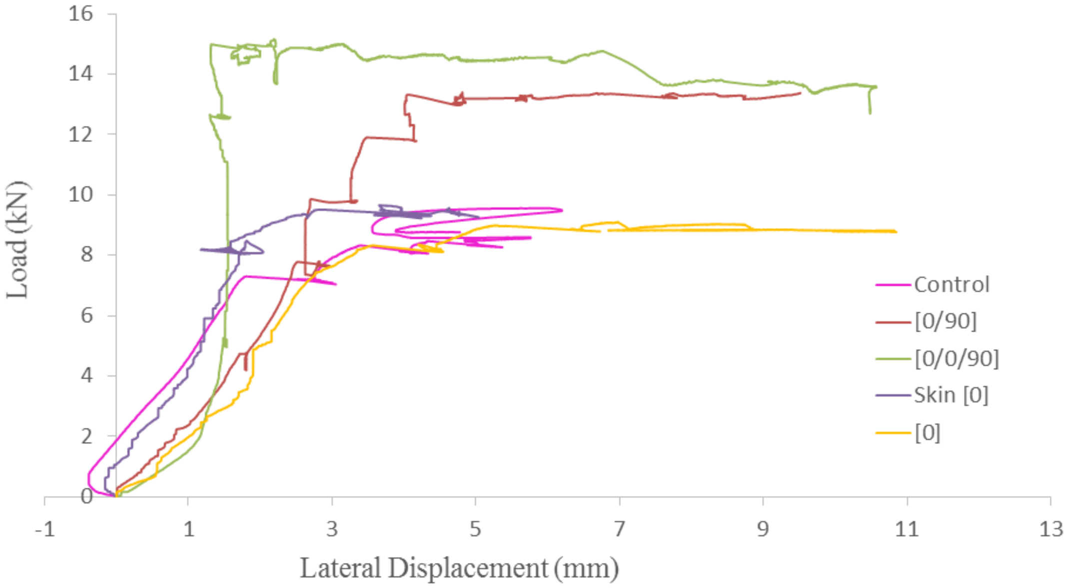


Figure 4.46: Set-B; Vertical load (P) vs Lateral Displacement (Dh)

For set-B typical behavior for all methods is compared in Fig. 4.46. For subset-3 (A50T5C2- $0^0/0^0/90^0$) and subset-2 (A50T5C1- $0^0/90^0$) significant strength gain in elastic as well as post yield zone is recorded over control specimen (subset-1), subset-4 (A50T5CR) and subset-5 (A50T5C0). For this set also in elastic region improved stiffening effect can be seen for subset-2 and 3. In post yield region for subset-2 stiffening effect is continued but for subset-3 there is drop in stiffening as observed in set-A for same configuration. It is mainly due to local debonding and quality control issues. From Fig. 4.46, for subset-4 (A50T5CR) and subset-5 (A50T5C0) it can be seen, there is no or little stiffening effect in elastic as well as post yield region in comparison with control specimens.

Figure 4.47, represents load vs lateral displacement for all subsets. It shows significant resistance offered by subset-3 (A50T5C2- $0^0/0^0/90^0$) and subset-2 (A50T5C1- $0^0/90^0$) to [LTB] in comparison with subsets 1, 4 and 5. A close look at fig. no. shows the stiffening offered by subsets -2 and 3 to LTB as there is significant increase in load for less or no increase in lateral displacement.

4.4 Comparison of ultimate load Pu

1. Set-A

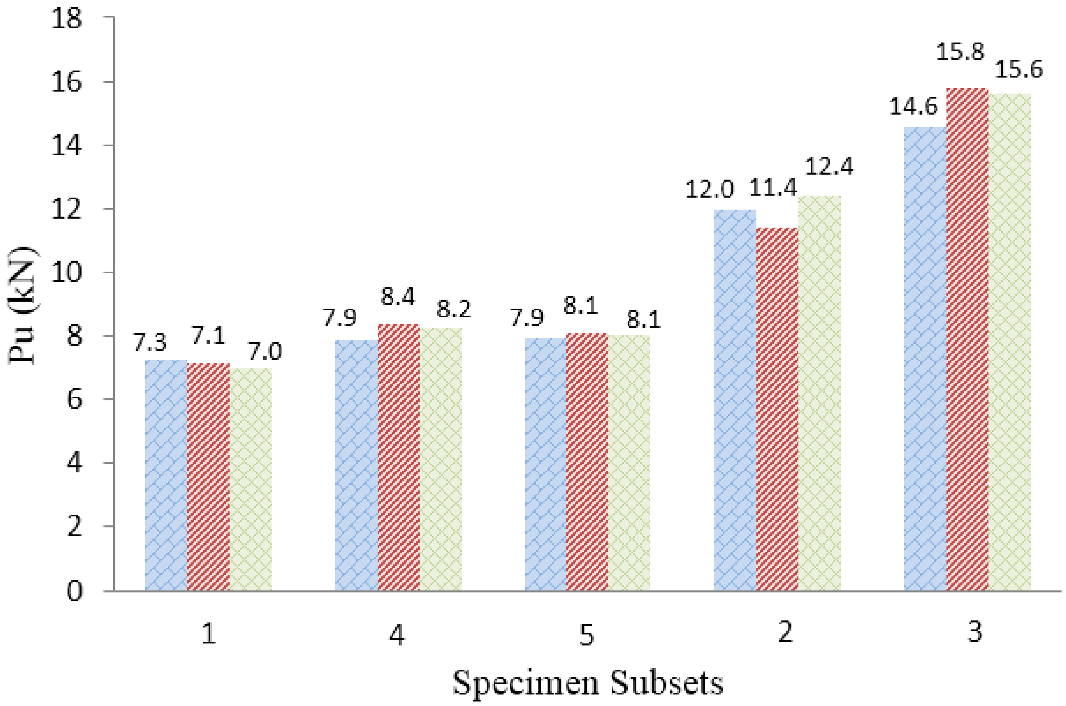


Figure 4.47: Set-A; Representation of of variation Pu

Table 4.6: Set A - Comparison of % increase of Pu

	Control Specimen A45T5	Wrapped Specimen A45T5C1	Wrapped Specimen A45T5C2	Externally bonded CFRP A45T5CR	Wrapped Specimen A45T5C0
	Subset1	Subset2	Subset3	Subset4	Subset5
Pu in kN	7.26	11.97	14.59	7.87	7.93
	7.15	11.40	15.79	8.38	8.10
	6.99	12.39	15.60	8.23	8.05
Mean % increase	**NA**	**67.16**	**114.91**	**14.40**	**12.56**
Maximum % increase	**NA**	**73.72**	**121.45**	**17.47**	**13.63**
Minimum % increase	**NA**	**59.89**	**104.52**	**10.32**	**11.15**

From fig. 4.48 and Table 5.1, it can be seen that there is significant increase of 121% in ultimate load Pu for subset-3 (A45T5C2- $0^0/0^0/90^0$) in comparison with control specimen subset-1. For subset-2 (A45T5C1- $0^0/90^0$), increase of 74% over control specimens observed. From Table 4.6, it can be seen that for subsets 4 and 5, there is increase of 17% and 13% in strength in comparison with subset-1. A clear difference of strength gain for the specimen subset-2 (74%) and subset-5 (13%) can be seen. It is mainly due to the hoop wrap (90^0) added for subsets-2 and subsets-3.

Table 4.7: Standard Deviation for set-A

	Ultimate Load Pu in kN			Standard Deviation
Subset1	7.26	7.15	6.99	**3.07**
Specimen No.	1	2	3	
Subset2	11.97	11.40	12.39	**5.48**
Specimen No.	4	5	6	
Subset3	14.59	15.79	15.60	**7.18**
Specimen No.	7	8	9	
Subset4	7.87	8.38	8.23	**3.59**
Specimen No.	10	11	12	
Subset5	7.93	8.10	8.05	**3.51**
Specimen No.	13	14	15	

Table 4.7, gives the standard deviation among subsets. It can be seen that except for subset -3 all other subsets are having standard deviation approximately under acceptable limits of 5. In case of subset-3, specimen 7 is quite off due to local debonding failure mode.

- **Set B**

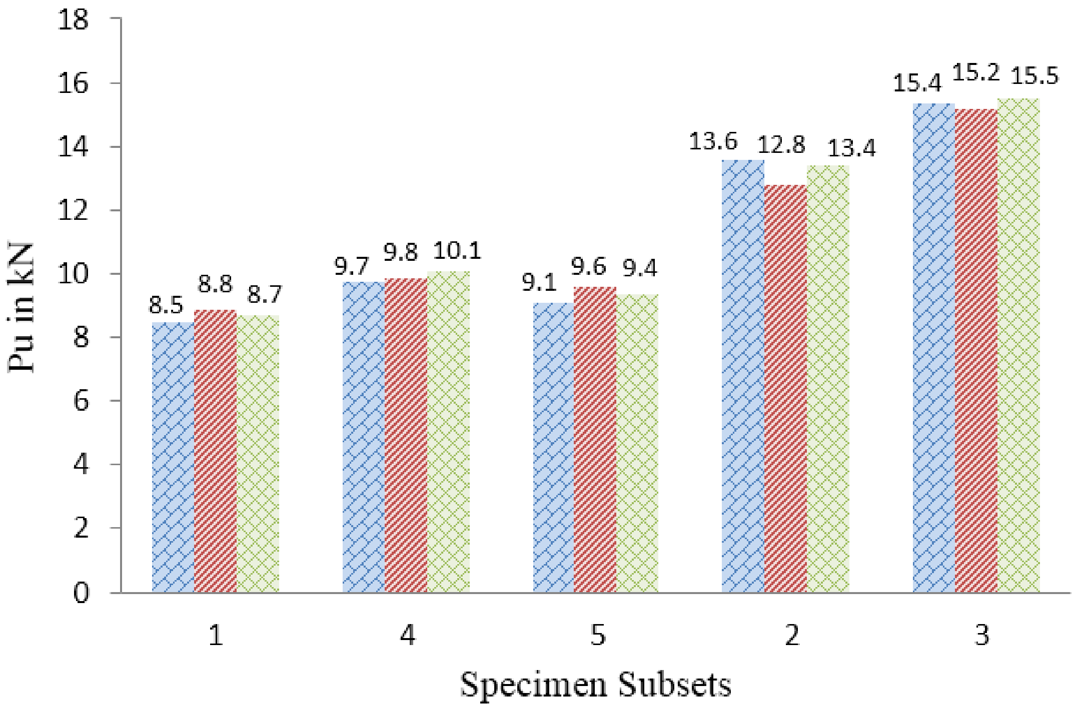


Figure 4.48: Set-B; Representation of of variation Pu

Table 4.8: Set A - Comparison of % increase of Pu

	Control Specimen A50T5	Wrapped Specimen A50T5C1	Wrapped Specimen A50T5C2	Externally bonded CFRP A50T5CR	Wrapped Specimen A50T5C0
	Subset1	Subset2	Subset3	Subset4	Subset5
Pu in kN	8.46	13.56	15.36	9.75	9.11
	8.84	12.78	15.16	9.84	9.56
	8.72	13.40	15.50	10.09	9.35
Mean % increase	**NA**	**52.73**	**76.89**	**14.10**	**7.67**
Maximum % increase	**NA**	**56.34**	**78.71**	**16.39**	**10.22**
Minimum % increase	**NA**	**47.37**	**74.83**	**12.40**	**4.98**

For set-B, from fig. 4.49, and Table 4.8, it can be seen that there is significant increase of 79% in ultimate load Pu for subset-3 (A50T5C2- $0^0/0^0/90^0$) in comparison with control specimen subset-1. This increase is not similar to increase observed in Set-A for same wrap configuration. It is mainly due to fabrication issue and local debonding under loading in post yield region. For subset-2 (A50T5C1-$0^0/90^0$), increase of 56% over control specimens observed. This increase is also not similar to the increase observed in Set-A for same wrap configuration. It is also mainly due to local debonding or delamination of CFRP. For subsets 4 and 5 it can be seen that there is no significant increase in Pu is observed.

But in comparison with subset 5 (10%), subset 1 has shown 56% of gain strength over control specimens. It is specifically due to the hoop wrap which is providing the confinement to the longitudinal wrap.

Table 4.9: Standard Deviation for set-B

	Ultimate Load Pu in kN			Standard Deviation
Subset1	8.46	8.84	8.72	**3.84**
Specimen No.	16	17	18	
Subset2	13.56	12.78	13.40	**6.13**
Specimen No.	19	20	21	
Subset3	15.36	15.16	15.50	**7.17**
Specimen No.	22	23	24	
Subset4	9.75	9.84	10.09	**4.45**
Specimen No.	25	26	27	
Subset5	9.11	9.56	9.35	**4.17**
Specimen No.	28	29	30	

Table 4.9, gives the standard deviation for subsets. It can be seen that except for subset - 2 and 3 all other subsets are having standard deviation approximately under acceptable limits of 5. In case of subset-2 and 3 standard deviation is more than 5 but less than 7.5. It is mainly due to local debonding failure mode.

4.5 Comparison of Moment vs Strain

Figure 4.50, shows comparison of moment vs strain (recorded at midspan) between control specimen subset-1 (specimen-1, [A45T5]) and skin strengthened specimen subset-4 (specimen-10, [A45T5CR]). Six strain gages were placed at midspan (see Fig 3.26) in both the control specimen and skin strengthened specimen at the same location. The solid lines in Fig. 4.49 indicate control specimen and the dotted lines refer to strengthened specimen. The control specimen It can be observed that the strains recorded for CFRP strengthened specimen (No.10) are lower than control specimen (No.1) by 36 %. This indicates that the strengthening of steel sections reduces the strain due to the composite action between the steel and CFRP. A close look at the graph shows that strain gages S1, S3 and S5 recorded compressive strains and gages S2, S4 and S6 recorded tensile strains. It should be noted that the strain gages 2 and 4 recorded tension since the specimens underwent lateral bending experiencing tensile stresses at the extreme fibers due to unsymmetrical bending of angle sections. (Type-1; gage location).

Figure 4.51, shows comparison of moment vs strain between subset-3 (A45T5C2- $0^0/0^0/90^0$) and subset-2 (A45T5C1- $0^0/90^0$). It can be seen that strain gages S1 and S2 for both CFRP configurations have recorded compressive strains unlike for control specimens (strain gage S2 recorded tensile strains, fig. 3.26). Also the gages S3 and S4 have recorded tensile strains unlike for control specimens ((strain gage S3 recorded tensile strains, fig. 3.26). This is a clear indication of change in failure pattern of vertical bending accompanied by twisting and lateral bending occurring simultaneously in subsets 1 and 4 (control and skin strengthened specimens) to predominantly vertical bending in subsets 2 and 3 ($0^0/90^0$ and $0^0/0^0/90^0$ specimens). This can be mainly attributed to transformation of open section (subsets 1 and 4) which exhibits unsymmetrical bending to closed section (subsets 2 and 3) which exhibits symmetrical bending. .

It can also be seen that for CFRP (A45T5C2- $0^0/0^0/90^0$) with two layers of unidirectional fibers there is significant reduction in strains in comparison with a single layer of unidirectional fiber (A45T5C1- $0^0/90^0$). Therefore, an additional layer of unidirectional CFRP decreases the strains considerably for higher load values at midspan. This may be due to use of high strength carbon fibers.

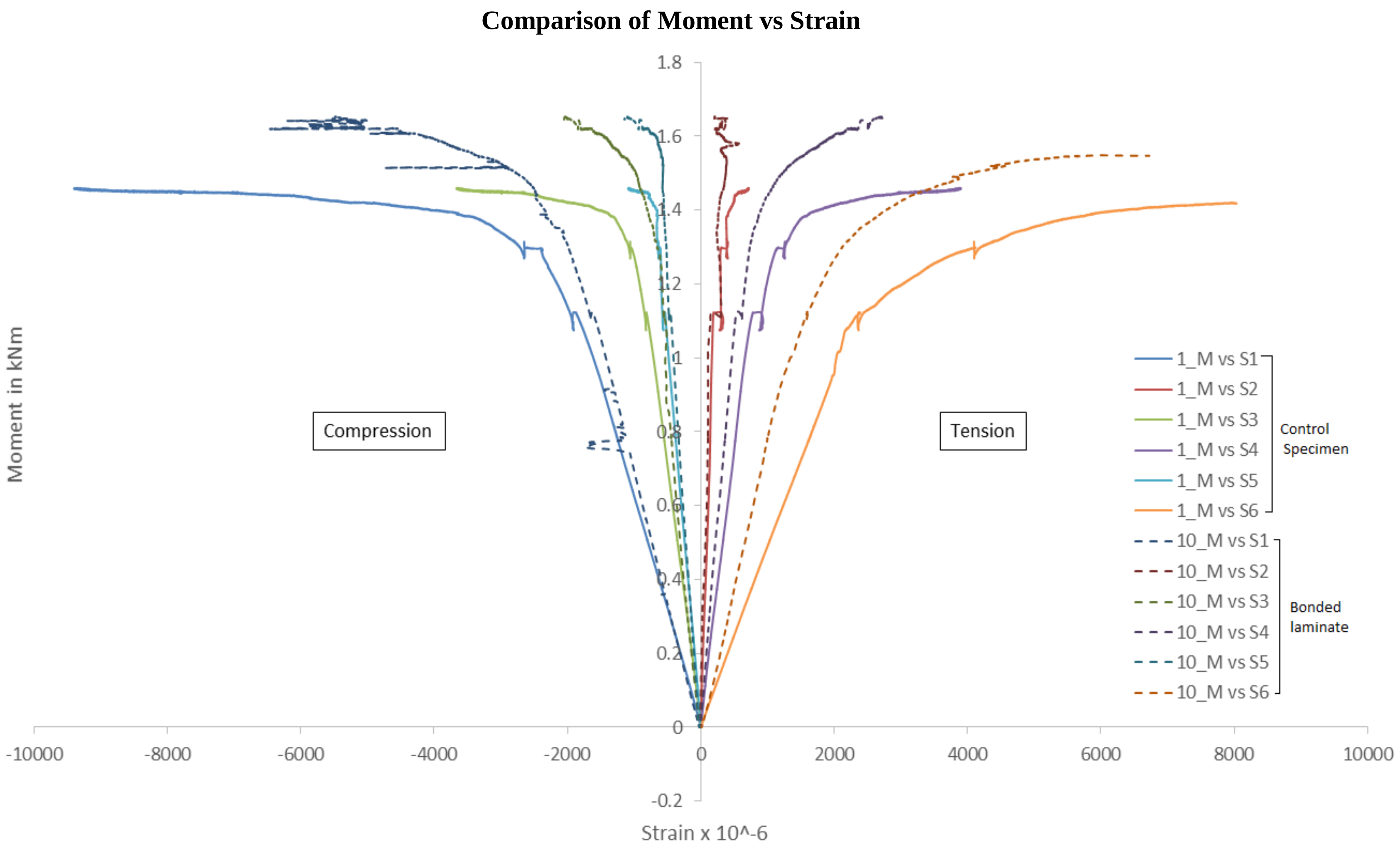


Figure 4.49: Moment vs Strain for specimen-1 and specimen-10 (Type-1; strain gage location)

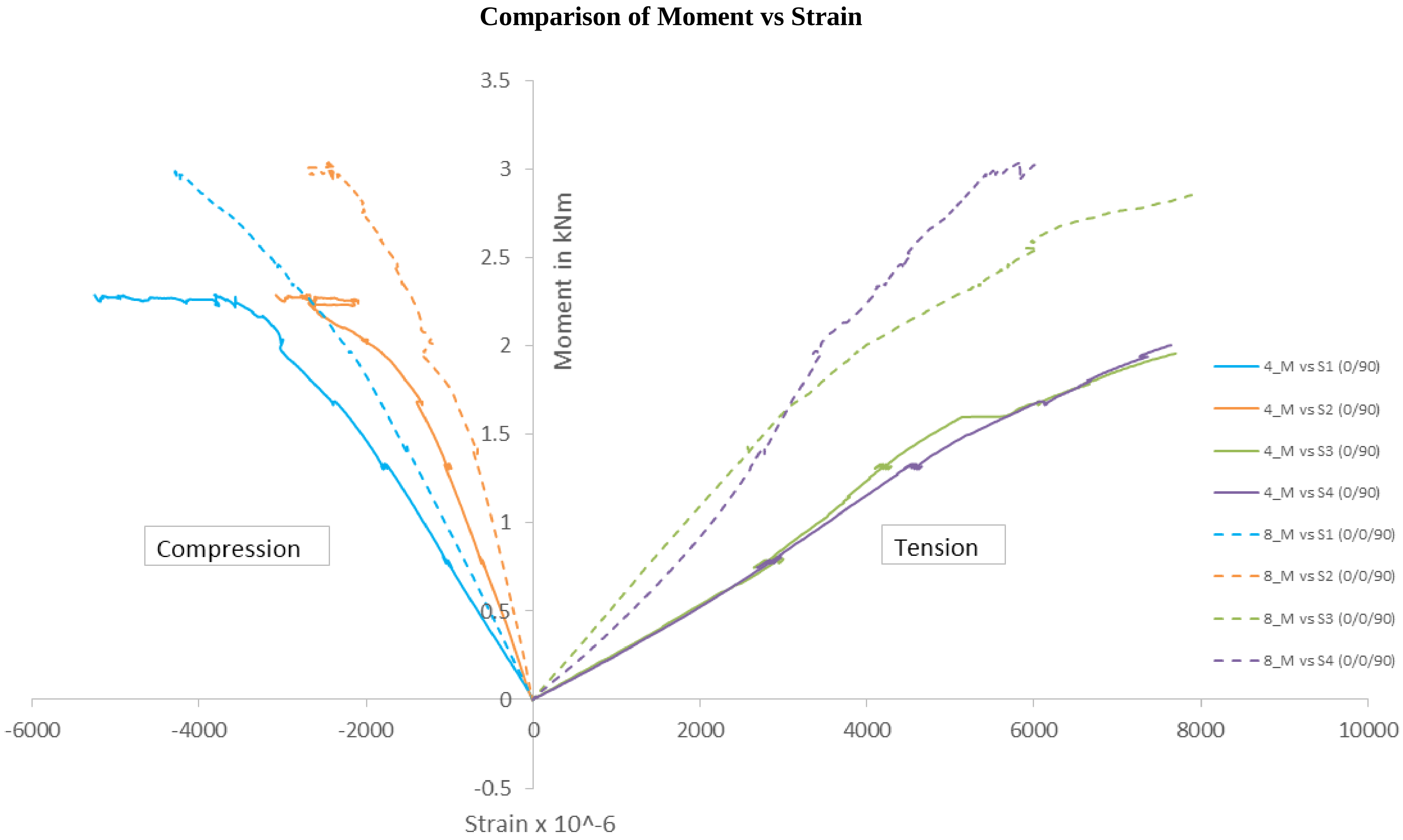


Figure 4.50: Moment vs Strain for specimen-4 and specimen-8 (Type-2; strain gage location)

4.6 Stress vs Strain for structural steel coupons

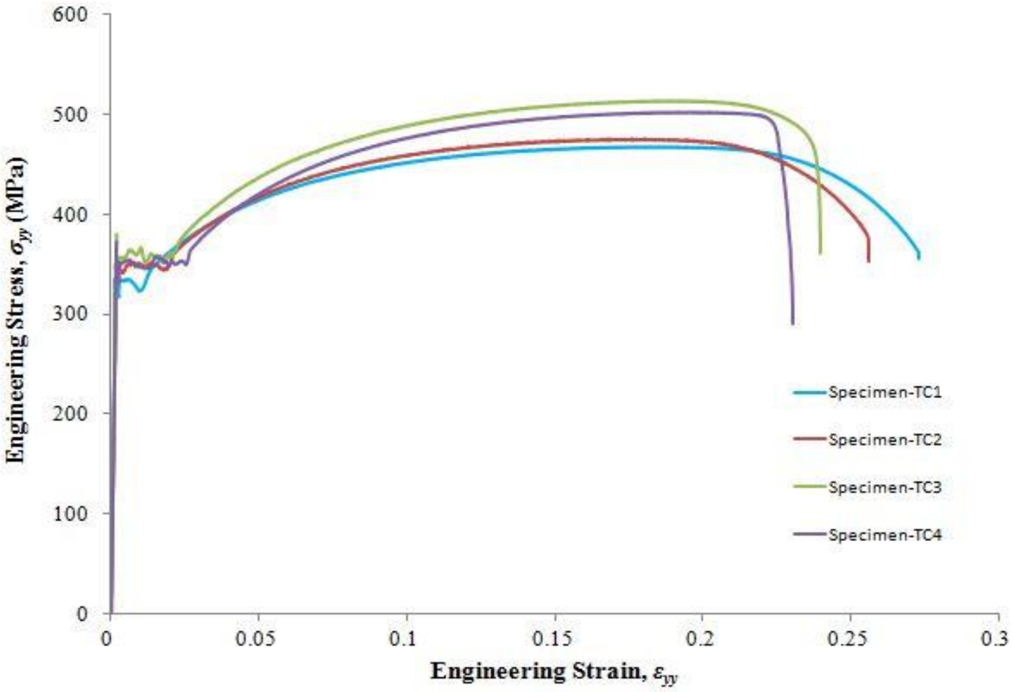


Figure 4.51: Engineering stress vs engineering strain for structural steel

A stress-strain curve of the tensile test coupon is shown in Fig. 4.52, in which a sharp change in yield point followed by plastic strain is observed. After a certain amount of the plastic deformation of the material, due to reorientation of the crystal structure an increase in stress is observed with increase in strain. This range is called the strain hardening range.

Figure 4.52: Tensile coupon test onset of fracture

After a slight increase in load, the specimen eventually fractures. After the failure it is seen that the fractured surface of the two pieces form a cup and cone arrangement. This cup and cone fracture is considered to be an indication of ductile fracture. Fig. 4.53 shows the onset of ductile failure. The nominal stress or the engineering stress is given by the load divided by the original area. Similarly, the engineering strain is taken as the ratio of the change in length to original length.

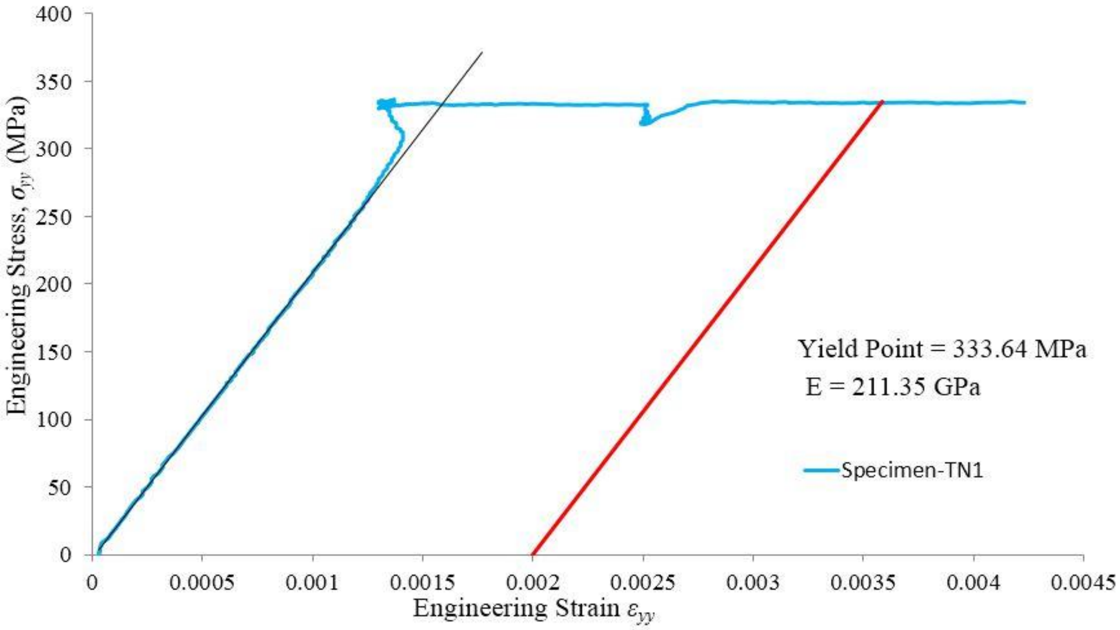


Figure 4.53: Stress vs Strain for specimen-TC1, offset method

For all specimens it was observed that due to instrumentation shortcoming there was reduction in strain values and no clear yield was available. So offset method of 0.2% proof stress is used to establish the elastic modulus and yield strength. Table 4.10 to 4.12; indicate the mechanical properties of all the coupons. It was found that the structural steel used for this research work is not 250 MPa mild steel. Its classification as per IS2062:2007, is given below.

Table 4.10: Grade of Structural steel as per IS2062

IS code	Grade	Yield stress (Mpa) ; min (for d or t)			Ultimate tensile stress (Mpa) min.	Elongation percentage
		<20	20-40	>40		
IS2062	Fe490	350	330	320	490	22

Table 4.11: Tensile test data -1

Specimen No.	Thickness	Width	Area	Elastic Modulus	Load At Offset Yield	Stress At Offset Yield	Load At Yield
	mm	mm	mm2	GPa	N	MPa	N
1TC	5.49	12.59	69.12	211.35	23060.84	333.64	23183.34
2TC	5.27	12.45	65.61	215.04	22500.05	342.93	23083.65
3TC	5.04	12.81	64.56	212.81	22969.18	355.77	23678.59
4TC	4.90	11.63	56.99	208.16	20000.42	350.96	20171.23
Mean	5.18	12.37	64.07		22132.62	345.82	22529.20
Standard deviation	0.26	0.52	5.11		1442.53	9.70	1593.37

Table 4.12: Tensile test data -2

Specimen No.	Stress At Yield	Peak Load	Peak Stress	Break Load	Break Stress	Young's Modulus
	MPa	N	MPa	N	MPa	GPa
1TC	335.41	32379.13	468.45	24593.36	355.81	211.35
2TC	351.82	31224.70	475.90	23145.66	352.77	215.04
3TC	366.76	33142.13	513.33	23285.74	360.67	212.81
4TC	353.96	28610.35	502.05	16511.15	289.74	208.16
Mean	351.99	31339.08	489.94	21883.98	339.75	
Standard deviation	12.87	1982.57	21.23	3640.73	33.50	

Chapter 5

Summary and Conclusion

5.1 Introduction

This research has investigated experimentally the various ways of strengthening steel angle sections. It is observed that the typical strengthening approach used for closed steel sections or concrete sections where the external skin is strengthened will not suffice for an open section such as an angle section. Steel angle sections are unique since they undergo unsymmetrical bending and it becomes important to choose a CFRP strengthening technique that will obviate undesirable failures. This is possible only if the strengthening technique will alter the cross section configuration to ensure a desirable mode of failure. In the present work, an approach is undertaken to convert the equal angle section which is an open section to a square section by providing an internal form work over which the CFRP can be wrapped thereby transforming bare steel angle section into a closed section.

The results obtained from the experiments clearly indicates that the approach undertaken to transform an open section (low torsional resistance) to closed one (high torsional resistance) by CFRP wrapping has significantly increased the strength and stiffness of the bare steel angle section. This also indicates that the effectiveness of CFRP can be enhanced by a simple change in cross section. The novel strengthening technique is probably the first of its kind to be applied to an angle section and studied experimentally. It has numerous applications in the real world due to the fact that a significant number of transmission towers in India and around the world use structural steel angle sections which are to be retrofitted.

5.2 Strengthening technology for open sections (wrapping technology)

This research has resulted in development of unique and new strengthening configuration for open sections (structural steel angle section) by transforming them into closed section thereby enhancing their resistance to lateral torsional buckling strength when subjected to four point bending. The improvement in strengthening scheme proposed can be a breakthrough for strengthening of different shapes available in steel structures. Our experience of working on the proposed wrapping scheme suggest that, with good strengthening instruments and quality control facilities, positive enhancement in strength and stiffness can be achieved.

5.3 Transformation of behavior from [FY+LTB] into [FY]

With a reference bare steel specimens subset, four distinct strengthening configurations were prepared and tested experimentally under four point bending setup. The findings of research indicate that use of CFRP wrap configurations namely ($0^0/90^0$) and ($0^0/0^0/90^0$) for strengthening of equal structural steel angle sections have resulted in significant transformation of [FY+LTB] behavior of open angle sections under four point bending into [FY] in its elastic region. The effectiveness of addition of hoop wrap (90^0) can be seen from the majestic improvement in the stiffening effect in elastic region as well as in post yield zone. It has effectively behaved as a confinement for longitudinal (0^0) wrap.

5.4 Failure modes

The failure mode of strengthened specimen with wrap configuration ($0^0/90^0$) was ductile and accompanied by considerable deformation in comparison with wrap configuration ($0^0/0^0/90^0$) (see Fig. 4.7) It is mainly due to local debonding at the interface of CFRP layers (first and second layer of CFRP). Also in comparison with control specimens and subsets-4 and 5, wrap configuration ($0^0/90^0$) shown ductile behavior in elastic region as well as in post yield region. For strengthened specimens with wrap configuration ($0^0/0^0/90^0$) and ($0^0/90^0$) failure started with debonding of local adjacent CFRP bond and then converted into debonding of steel and CFRP interface which lead to rupture of (0^0) CFRP wrap layer on tension face (see Table 4.4). Upto this strengthened specimens have shown enhanced resistance to LTB.

After complete debonding inside flexure zone, strengthened specimens went into behavior mode of control specimens. For strengthened specimens with wrap configuration (0^0) failure started with delamination of CFRP on sideways on cardboard (see Fig. 4.22). Then lead to debonding of CFRP from steel interface and ended up with LTB. No prominent change of behavior observed for subset-5. Same is the case with subset-4 externally bonded specimens, failure started with debonding of CFRP from steel interface lead to rupture of fibers due to excessive strains and loss of composite action. Then it ended up with very little resistance to LTB. So the research objective of transformation of open section into closed section by transforming [FY+LTB] into [FY] has been achieved for wrap configurations ($0^0/0^0/90^0$) and ($0^0/90^0$).

5.5 Strength enhancement

The load carrying capacity up to the yielding of steel in beams can be significantly increased through use of high strength CFRP wrapping configurations proposed (see Fig. 4.44). Especially for strengthening of open sections existing strengthening configurations (subset-4) haven't shown significant increment in strength over control specimens. Increase in elastic stiffness is significant for both wrap configurations ($0^0/0^0/90^0$) and ($0^0/90^0$). These findings are having significant potential for strengthening of steel structures for increased service loads.

5.6 Moment capacity enhancement

25% to 40% strain reduction is achieved for strengthened specimens with wrap configurations ($0^0/0^0/90^0$) and ($0^0/90^0$) with enhanced moment carrying capacity (see Fig. 4.51) in elastic region as well as post yield region.

5.7 Thickness or no. of layers of CFRP wraps or laminates

Tavakkolizadeh and Saadatmanesh (2003) investigated the behavior of steel-concrete composite girders strengthened with CFRP sheets under static loading. As per their research, ultimate load-carrying capacity of girders, significantly increased by 44, 51, and 76% for one-, three-, and five-layer retrofitting configurations. Test results for specimens strengthened with wrap configurations ($0^0/0^0/90^0$) and ($0^0/90^0$)

have shown significant increase in ultimate load carrying capacities by 122% and 74% (set A results) over control specimens. It is reported that as the number of CFRP layers increased, the efficiency for utilizing the CFRP layers decreased. Test result for ($0^0/90^0$) wrap configuration indicated that ultimate strength increased by 52.96% in comparison with wrap configuration (0^0). This is mainly due to the hoop wrap which provided effective confinement to longitudinal wrap. So the research carried out suggest that instead of increasing the layers of CFRP alike done by Tavakkolizadeh et al, confinement wrap can be provided. Test results for wrap configurations ($0^0/0^0/90^0$) indicated increment of 27% ultimate strength in comparison ($0^0/90^0$) wrap configuration.

5.8 Lateral Stability

Enhanced lateral stability observed in strengthened specimens with hoop wrap configuration (see Fig. 4.51). In elastic region, the strains reported on tension side have shown uniformity.

5.9 Effect of strengthening on slenderness ratio (b/t)

No significant result recorded for slenderness ratio parameter in case of comparison between set A and set B. Reduction in percentage ultimate strength increment between Set A and Set B results observed. It is mainly due to quality control issue. As most specimens in set B shown premature failure due to local debonding in post yield region even after behaving excellent in elastic region. For set B, it was found that the quantity of epoxy adhesive used was more than set A. Also proper rolling was not happened which entrapped air and resulted in voids and lack of proper bonding with parent specimen’s steel.

Chapter 6

Future work

External wrapping (bonded) of CFRP reinforcement (breakthrough [longitudinal + hoop wrap] configuration proposed) to structural steel angle sections has been clearly established and investigated experimentally as a promising effective strengthening technique for steel structures as an alternative to existing methods of strengthening configurations. As more research will be conducted and more reliable measures of strengthening available, the technique is also expected to receive audacious acceptance in practice.

The present investigation evaluated experimentally, the effectiveness of wrap configuration proposed to transform behavior of open sections into closed section, stiffening enhancement in elastic region and strength enhancement in both elastic and post yield regions of high strength CFRP strengthened structural steel angles tested under four point bending system in comparison with bare steel angles. During course of study and research on strengthening of distinct sections used in steel structures, numerous areas were identified which shall require future investigation.

- CFRP material characterization - The present tests showed that the bond failed in tensile failure (flexure) of the adhesive epoxy rather than in shear. The factors affecting this type of failure, properties of the epoxy adhesive as well as the laminates should be verified and established both experimentally and analytically.
- Sequence of wrap configuration – A new wrap configuration ($0^0/90^0/0^0/90^0$) shall be tried to investigate the strength and stiffness enhancement.
- Surface preparation - In depth work should be conducted on pretreatment of steel surface preparation and its characterization at micro level to establish a widely acceptable procedure for field application to avoid adhesion failure at steel/adhesive interface.
- Debonding failure and bond behavior - The most challenging issues observed in flexural strengthening of structural steel are debonding failures against local buckling and local debonding. Weak link in FRP strengthened structures is

adhesive and debonding failure depends on properties of adhesive. So study of distinct adhesive material models experimentally as well as analytically should be done. A special attention should be paid to the local debonding on compression side as literature review reveals very little or no research on this front.

- Buckling of columns - As angle sections are predominantly used as bracing members in steel structures, a fresh experimental research should be done on enhancement of buckling strength with proposed wrap configurations. Study on transformation of failure mode from sudden collapse to ductile failure should be investigated with the proposed wrap configuration.
- Ultra high modulus and High modulus Carbon fibers - The experimental results with proposed wrap configuration by using high strength carbon fibers should be compared with specimens prepared with ultra high modulus and high modulus carbon fiber to establish a comparative study among high strength, ultra high modulus carbon fiber and high modulus carbon fiber.
- Durability Study - The effect of fatigue and also environmental effects on the performance of the steel - CFRP wrap bond interface was not addressed in this study, and very few studies have been carried out in this area. More research should be performed on both of these areas to improve understanding of the bond interface.
- CFRP wrap optimization - Optimization of CFRP wrap has not been addressed in this study. An investigation by using hoop wraps at certain spacing’s as a confinement alike done in RCC; stirrups are used to confine the concrete should be carried out to establish the parametric study inputs and optimization of CFRP material requirement.
- Improvement of Internal formwork - In present study card board sheets have been used as an internal formwork, which was resulted in absorption of adhesive and reduction in matrix for CFRP. So study should be carried out use some other materials like, wood, aerosol, thermocol, plastic thin sheets etc. to establish the results.
- Field application - Apply the proposed wrap configuration to in use transmission towers or pipe rack structures and carry out the health monitoring study.

- Field application optimization study - The wrapping scheme should be made robust and improved to match the field requirements like wrapping time optimization, safety precautions, optimization of utility skilled workers requirement etc.
- Several other topics which are not directly related but the proposed wrap configuration should be investigated to establish understanding about behavior as like; fire resistance of strengthened steel structures, strengthening of steel structures against blast and impact loading, use and efficiency of CFRP confinement hoop wrap for combined strengthening and corrosion.

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