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Experimental and Analytical Study on Torsional Behavior of RC Flanged Beams with Strengthened with Glass FRP

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***Abstract*: Environmental degradation, increased service loads, reduced capacity due to aging, degradation owing to poor construction materials and workmanships and conditional need for seismic retrofitting have demanded the necessity for repair and rehabilitation of existing structures. Fibre reinforced polymers has been used successfully in many such applications for reasons like low weight, high strength and durability. Many previous research works on torsional strengthening were focused on solid rectangular RC beams with different strip layouts and different types of fibres. Various analytical models were developed to predict torsional behavior of strengthened rectangular beams and successfully used for validation of the experimental works. But literature on torsional strengthening of RC T- beam is limited. In the present work experimental study was conducted in order to have a better understanding the behavior of torsional strengthening of solid RC flanged T-beams. An RC T-beam is analyzed and designed for torsion like an RC rectangular beam; the effect of concrete on flange is neglected by codes. In the present study effect of flange part in resisting torsion is studied by changing flange width of controlled beams. The other parameters studied are strengthening configurations and fiber orientations.**

***Keywords*: Torsional behavior, RC flanged beams, Glass FRP.**

1. Introduction

Modern civilization relies upon the continuing performance of its civil engineering infrastructure ranging from industrial buildings to power stations and bridges. For the satisfactory performance of the existing structural system, the need for maintenance and strengthening is inevitable. During its whole life span, nearly all engineering structures ranging from residential buildings, an industrial building to power stations and bridges faces degradation or deteriorations. The main causes for those deteriorations are environmental effects including corrosion of steel, gradual loss of strength with ageing, variation in temperature, freeze-thaw cycles, repeated high intensity loading, contact with chemicals and saline water and exposure to ultra- violet radiations. Addition to these environmental effects earthquakes is also a major cause of deterioration of any structure. This problem needs development of successful structural retrofit technologies. So it is very important to have a check upon the continuing performance of the civil engineering infrastructures. The structural retrofit problem has two options, repair/retrofit or demolition/ reconstruction. Demolition or reconstruction means complete replacement of an existing structure may not be a cost-effective solution and it is likely to become an increasing financial burden if upgrading is a viable alternative. Therefore, repair and rehabilitation of bridges, buildings, and other civil engineering structures is very often chosen over reconstruction for the damage caused due to degradation, aging, lack of maintenance, and severe earthquakes and changes in the current design requirements.

2. Torsional strengthening of beams

Early efforts for understanding the response of plain concrete subjected to pure torsion revealed that the material fails in tension rather than shear. Structural members curved in plan, members of a space frame, eccentrically loaded beams, curved box girders in bridges, spandrel beams in buildings, and spiral stair-cases are typical examples of the structural elements subjected to torsional moments and torsion cannot be neglected while designing such members.

Structural members subjected to torsion are of different shapes such as T-shape, inverted L–shape, double T-shapes and box sections. These different configurations make the understanding of torsion in RC members of complex task. In addition, torsion is usually associated with bending moments and shearing forces, and the interaction among these forces is important. Thus, the behaviour of concrete elements in torsion is primarily governed by the tensile response of the material, particularly its tensile cracking characteristics. Spandrel beams, located at the perimeter of buildings, carry loads from slabs, joists, and beams from one side of the member only. This loading mechanism generates torsional forces that are transferred from the spandrel beams to the columns. Reinforced concrete (RC) beams have been found to be deficient in torsional capacity and in need of strengthening. These deficiencies occur for several reasons, such as insufficient stirrups resulting from construction errors or inadequate design, reduction in the effective steel area due to corrosion, or increased demand due to a change in occupancy. Similar to the flexure and shear strengthening, the FRP fabric is bonded to the tension surface of the RC members for torsion strengthening. In the case of torsion, all sides of the member are subjected to diagonal tension and therefore the FRP sheets should be applied to all the faces of the member cross section.

3. Experimental study

T-shaped beams, which are sorted in three groups (T2, T3 and T4) and were tested under combined bending torsion. Three numbers of beams are without torsional reinforcement were the control specimens and eight specimens were strengthened using epoxy-bonded glass FRP fabrics as external transverse rein-forcemeat. The cross-section of specimens was One beam were flanged beams with T-shaped with dimensions $b_w/D/b_f/d_f$ = 150/270/250/80 mm (beams of series T2). In the series-B five beam specimens were flanged beams, and they dimensions are $bw/D/b_f/d_f$=150/270/350/80 (beams of series T3). And also another five beam specimens were T-shaped cross- section and dimensions $b_w/D/b_f/d_f$ =150/270/350/80 (beams of series T4). The cross-section of all beams. Each group comprises one control specimen without transverse reinforcement. Specimens T2C were the control specimen of group-A, it had only longitudinal reinforcement; four deformed bars of diameter 20mmφ, and 10mmφ, at the corners of the cross-section, and control specimen of T3C, and T4C of series six longitudinal deformed bars of diameter 20 mmφ, 10mmφ, and 8mmφ, transverse bars of 8mmφ two legged stirrups. The other eight specimens of the experimental program included the same longitudinal reinforcement as the control specimens of their group and transverse rein- forcement (steel stirrups).

4. Casting of specimens

For conducting experiment, eleven reinforced concrete beam specimen of size as Shown in the fig (Length of main beam (L) = 1900mm, Breadth of main beam(bw) = 150mm, Depth of main beam(D) = 270mm, Length of cantilever parts = 400mm, Width of cantilever part= 200mm, Depth of cantilever part= 270mm, Distance of cantilever part from end of the beam= 350mm) and all having the same reinforcement detailing are cast. The mix proportion is 0.5: 1:1.67:3.3 for water, cement, fine aggregate and course aggregate is taken. The mixing is done by using concrete mixture. The beams were cured for 28 days. For each beam three cubes, two cylinders and two prisms were casted to determine the compressive strength of concrete for 28 days.

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A. Fiber Reinforced Polymer (FRP)

Continuous fiber reinforced materials with polymeric matrix (FRP) can be considered as composite, heterogeneous, and anisotropic materials with a prevalent linear elastic behaviour up to failure. Normally, Glass and Carbon fibers are used as reinforcing material for FRP. Epoxy is used as the binding material between fiber layers. For this study, GFRP sheet was used during the tests i.e., a bidirectional FRP with the fiber oriented in both longitudinal and transverse directions, due to the flexible nature and ease of handling and application, the FRP sheets are used for torsional strengthening. Throughout this study, E-glass was used manufactured by Owens Corning.

B. Epoxy resin

The success of the strengthening technique primarily depends on the performance of the epoxy resin used for bonding of FRP to concrete surface. Numerous types of epoxy resins with a wide range of mechanical properties are commercially available in the market. These epoxy resins are generally available in two parts, a resin and a hardener. The resin and hardener used in this study are Araldite LY 556 and hardener HY 951 respectively.

5. Casting of GFRP plate for tensile strength

There are two basic processes for moulding, that is, hand lay-up and spray-up. The hand lay-up process is the oldest, simplest, and most labour intense fabrication method. This process is the most common in FRP marine construction. In hand lay- up method liquid resin is placed along with reinforcement (woven glass fiber) against finished surface of an open mould. Chemical reactions in the resin harden the material to a strong, light weight product. The resin serves as the matrix for the reinforcing glass fibers, much as concrete acts as the matrix for steel reinforcing rods. The percentage of fiber and matrix was 50:50 by weight. The following constituent materials are used for fabricating the GFRP plate:

1. Glass FRP (GFRP)
2. Epoxy as resin
3. Hardener as diamine (catalyst)
4. Polyvinyl alcohol as a releasing agent

Fig. 1. Specimens for tensile testing of woven glass/epoxy composite

Fig. 2. Experimental setup of instron (UTM)

Fig. 3. Specimen during testing

A. Determination of ultimate stress, ultimate load & young's modulus of FRP

The ultimate stress, ultimate load and young's modulus was determined experimentally by performing unidirectional tensile tests on specimens cut in longitudinal and transverse directions. The specimens were cut from the plates by diamond cutter or by hex saw. After cutting by hex saw, it was polished with the help of polishing machine. At least three replicate sample specimens were tested and mean values adopted. For measuring the tensile strength and young's modulus, the specimen is loaded in INSTRON600 kN in Production Engineering Lab, NIT, Rourkela. Specimens were gripped in the fixed upper jaw first and then gripped in the movable lower jaw. Gripping of the specimen should be proper to prevent the slippage. Here, it is taken as 50 mm from each side. Initially, the strain is kept zero. The load, as well as the extension, was recorded digitally with the help of a load cell and an extensometer respectively. From these data, stress versus strain graph was plotted, the initial slope of which gives the young's modulus. The ultimate stress and ultimate load were obtained at the failure of the specimen.

6. Strengthening of beams

At the time of bonding of fiber, the concrete surface is made rough using a coarse sand paper texture and then cleaned with an air blower to remove all dirt and debris. After that the epoxy resin is mixed in accordance with manufacturer's instructions. The mixing is carried out in a plastic container (100 parts by weight of Araldite LY 556 to 10 parts by weight of Hardener HY 951). After their uniform mixing, the fabrics are cut according to the size then the epoxy resin is applied to the concrete surface. Then the GFRP sheet is placed on top of an epoxy resin coating and the resin is squeezed through the roving of the fabric with the roller. Air bubbles entrapped at the epoxy/concrete or an epoxy / fabric interface are eliminated. During hardening of the epoxy, a constant uniform pressure is applied to the composite fabric surface in order to extrude the excess epoxy resin and to ensure good contact between the epoxy, the concrete and the fabric. This operation is carried out at room temperature. Concrete beams strengthened with glass fiber.

Fig. 4. Application of epoxy and hardener on the beam

Fig. 5. Roller used for the removal of air bubble

7. Experimental setup

The beams were tested in the loading frame of "Structural Engineering" Laboratory of National Institute of Technology, Rourkela. The testing procedure for the all the specimen is same. First the beams are cured for a period of 28 days then its surface is cleaned with the help of sand paper for clear visibility of cracks. The two - point loading arrangement was used for testing of beams. This has the advantage of a substantial region of nearly uniform moment coupled with very small shears, enabling the bending capacity of the central portion to be assessed. Two-point loading is conveniently provided by the arrangement shown in Figure 3.9. The load is transmitted through a load cell and spherical seating on to a spreader beam. The spreader beam is installed on rollers seated on steel plates bedded on the test member with cement in order to provide a smooth levelled surface. The test member is supported on roller bearings acting on similar spreader plates. The specimen is placed over the two steel rollers bearing leaving 150 mm from the ends of the beam. The load is transmitted through a load cell via the square plates kept over the flange of the beam at a distance 100mm from the end. Loading was done by Hydraulic

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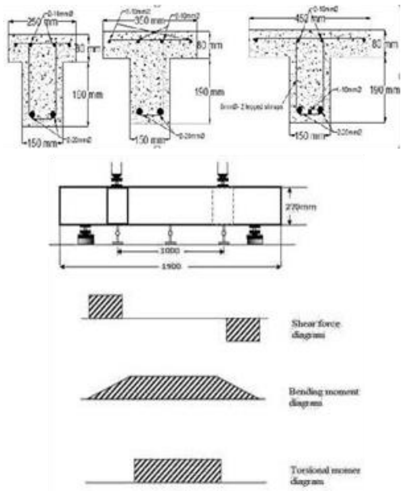

Fig. 6. Shear force and bending moment diagram for two-point loading

8. Failure modes

Different failure modes have been observed in the experiments. These include torsional shear failure due to GFRP rupture and debonding. Rupture of the FRP strips is assumed to occur if the strain in the FRP reaches its design rupture strain before the concrete reaches its maximum usable strain. GFRP debonding can occur if the force in the FRP cannot be sustained by the substrate. Load was applied on the two moment arm of the beams which is 0.375m away from the main beam. At each increment of the load, deflections at L/3, L/2 and 2L/3 were observed and noted down with the help of six nos. of dial gauges. At each section two dial gauges were fixed to measure the displacement caused by twisting moment. The relative displacements divided by distance between dial gauges gives angle of twist. Section at L/3 was taken as sec-1, section at middle of beam as taken as sec-2, and section at 2L/3 was taken as section 3. The loading arrangement was same for all the beams.

9. Torsional moment and angle of twist analysis

Torsional moment and Angle of twist Analysis of all Beams: Here the angle of twist of each beam is analyzed. Angle of twist of each beam is compared with the angle of twist of control beam. Also the torsional behaviors compared between different wrapping schemes having the same reinforcement. Same type of load arrangement was done for all the beams. All the beams were strengthened by application of GFRP in four layers over the beams. It was noted that the behavior of the beams strengthen with GFRP sheets are better than the control beams. The deflections are lower when beam was wrapped externally with GFRP strips. The use of GFRP strips had effect in delaying the growth of crack formation. When all the wrapping schemes are considered it was found that the Beam with GFRP strips fully wrapped and 45º orientation over full a length of 0.8m in the middle part had a better resistant to torsional behavior as compared to the others strengthened beams with GFRP.

Fig. 7. A Closed view of crack

Fig. 8. Crack in web portion

A. Torsional moment vs. Angle of twist curves

In this experiment load was applied on the two moment arm of the beams which is 0.35m away from the main beam and at each increment of the load, deflection at L/3, L/2 and 2L/3 is taken with the help of dial gauges. Using this load and deflection data, the corresponding torsion moment and the twisting angle were calculated and the above graph was plotted. In this group also the maximum ultimate strength was contributed by fully wrapped pattern of GFRP (T4SF). And complete wrapping scheme provided an efficient confinement and in turn a significant increase in ultimate strength was observed, the increase in strength was 107.23% as compared with the control beam (T4C). T4S45 also giving the increase in ultimate strength of 95.39% as compared with T4C. The U-wrapped beam T4SU showed increase in ultimate strength by 36.84 % with respect to control beam T4C whereas the beam with anchor bolts T4SUA showed 61.83% increase in ultimate strength. The bolts provide continuity to shear flow path hence more capacity to resist the torsion. The beam T4SUA indicated more ductile behavior compared with T4SU.

10. Conclusion

The experimental program of this study consists of eleven numbers of reinforced concrete T- beams with different flange widths tested under torsion. The main objective of this study is to investigate the effectiveness of the use of epoxy-bonded FRP fabrics as external transverse reinforcement. Based on presented experimental measurements and analytical predictions, the following conclusions were reached. Experimental results shows that the effect of flange width on

Table 1
Torsional capacity of Beams

Beam Description	Beam Designation	Ultimate load in kN	Ultimate Torsional Moment in kN-m	Type of Failure	Remark
Series T2	T2C	102	16.88	Debonding	First hair line crack appeared @80KN
	T3C	116	18.75	Debonding	First hair line crack appeared @90KN
	T3SU	143	26.81	Debonding	First hair line crack appeared @110KN
	T3SF	230	43.13	Debonding	First hair line crack appeared @210KN
Series T3	T3S45	210	39.375	Debonding	First hair line crack appeared @190KN
	T4C	152	28.50	Debonding	First hair line crack appeared @120KN
	T4SU	208	39.00	Debonding	First hair line crack appeared @160KN
Series T4	T4SF	315	58.13	Debonding	First hair line crack appeared @260KN
	T4S45	297	56.25	Debonding	First hair line crack appeared @230KN

Table 2
Comparison of Analytical and Experimental Results

Beam Name		t_f (mm)	n	θ	B	f_c 2 N/mm	^{T}f, cal kN m	^{T}fexp= Tult* - Tcont* kNm	
Series-A	T3SU	2.26	5	65º	90º	28.62	28.61	27	0.94
	T3SF	2.51	5	50º	90º	28.69	109.61	114	1.04
	T3S45	2.46	4	55º	45º	28.69	99.69	94	0.94
Series-B	T4SU	2.43	5	55º	90º	30.89	51.3	56	1.09
	T4SF	2.53	5	45º	90º	30.77	149.98	163	1.08
	T4S45	2.28	4	42º	45º	29.83	133.17	145	1.08

torsional capacity of GFRP strengthened. Torsional strength increases with increase in flange area irrespective of beam strengthening with GFRP following different configurations schemes.

With 250 mm wide flange width increase in strength was 13%, with 350mm wide flange was 29% and for 450mm wide flange was found to be 69%. This is due to increase in area enclosed inside the critical shear. The cracking and ultimate torque of all strengthen beams were greater than those of the control beams. The increase in magnitude depends on the FRP strengthening configurations. The present experimental program consisting of nine numbers of reinforced concrete T-beams with three different flange widths tested under torsion.

The main objective is to examine the effectiveness of epoxy-bonded GFRP fabrics used as external transverse reinforcement to resist torsion. Based on presented experimental results and analytical predictions, the following conclusions are drawn. i. Experimental results show that the effect of flange width on torsional capacity of GFRP strengthened RC T-beams are significant. ii. Torsional strength increases with increase in flange area irrespective of beam strengthening with GFRP following different configurations schemes.

With 250 mm wide flange width increase in strength was 13%, with 350mm wide flange was 29% and for 450mm wide flange was found to be 69%. This is due to increase in area enclosed inside the critical shear path. iv. The cracking and ultimate torque of all strengthen beams were greater than those of the control beams. v. The maximum increase in torque was obtained for 900fully wrapped configurations. Increase of 133.33% to 116.67% in first cracking and 155.55% to 107.23% in ultimate torsion were recorded for series T3 beams and series T4 beams respectively. vi. Beams fully wrapped with 450 oriented GFRP stripes showed next highest torsional resisting capacity. Increase of 111.11% to 91.667% in first cracking and 81.03% to 95.39% in ultimate torsion were recorded for series T3 beams and series T4 beams respectively.

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