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# *Torsional Strengthening of RC Beams with CFRP Wrap*

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## Abstract

Many studies have been performed in recent years on strengthening RC (reinforced concrete) beams in shear and bending using FRP (Fiber Reinforced Polymer) wraps and laminates. Torsional strengthening, however, has not attracted as much attention. The current study on the torsional strengthening of reinforced concrete beams was performed on reinforced concrete beams wrapped by CFRP (Carbon Fiber Reinforced Polymer). Several different configurations were used for the CFRP and the torque-twist angle paths of the beams were recorded to failure. The failure modes and the increase in the torsional strengths are presented in this paper.

**Keywords**: Beams; Concrete; Fiber-Reinforced Polymers (FRP); Strengthening; Tests; Torsion.

## تقوية الالتواء للعتبات الخرسانية المسلحة باللدائن المعززة بالياف الكاربون

### الخلاصة

انجزت الكثير من الدراسات في السنوات الاخيرة عن تقوية العتبات الخرسانية المسلحة لتحسين مقاومتها في القص والانحناء باستخدام اللدائن المعززة بالالياف. اما تقوية العتبات الخرسانية المسلحة لتحسين مقاومتها في الالتواء فان الاهتمام به من قبل الباحثين كان قليلا جدا. الدراسة الحالية تتحرى عن سلوك الالتواء للعتبات الخرسانية المسلحة والمقواة باللدائن المعززة بالياف الكاربون. استخدمت عدة اشكال من انماط التسليح باللدائن المعززة بالياف الكاربون واستخلصت النتائج من الفحوصات المختبرية والتي تشمل مقاومة الالتواء وزاوية الالتواء ومقدار التحسن في مقاومة الالتواء وشكل الفشل النهائي للعتبات.

## Introduction

Strengthening techniques for building structures have been developed for many years in order to lengthen the serviceability period under rapidly increased loading requirements and severe environmental conditions. Therefore, more economic and effective strengthening techniques for building structures have been particularly needed to increase the capacities of structural members damaged by deterioration and overloads. One of the most widely used repairing and retrofitting materials is epoxy bonded fiber reinforced polymer (FRP) sheet, due to its high strength and lightweight and its simple installation method.

Despite them gaining popularity, there is yet more research to be done to fully understand their behavior in particular applications. One can find a significant amount of research output in the literature in areas of shear and flexural strengthening but some areas like torsional strengthening and the effect of FRPs on beam-column joints are yet to be fully addressed.

In the area of torsional strengthening to which the current study is dedicated, there seems to be a shortage of convincing experimental and theoretical studies.

The objective of the present experimental study is to evaluate the effectiveness of the use of epoxy-bonded carbon FRP fabrics as external reinforcement to reinforced concrete beams with rectangular cross-section subjected to pure torsion. Torsional results from four strengthened beams are compared with the experimental data of control unstrengthened beam.

## Previous Studies

As mentioned earlier, most of the investigations on externally bonded FRP sheets were focused on flexural and shear strengthening of reinforced concrete members, reference to which can be found in Khalifa et al.[1] and Triantafillou[2].Unlike that, there are not as many investigations on torsional strengthening of beams. The few that exist are explained in the following.

Ghobarah et al.[3] experimentally investigated the effectiveness of carbon and glass FRP sheets and strips as additional external reinforcement to rectangular beams under torsion, and simple design approaches were also discussed. Salom et al.[4] studied experimentally and analytically the torsional behavior of six spandrel beams, which had been strengthened with FRP laminates using a special anchoring system. Both studies addressed that, in general, FRP materials caused a significant increase on the torsional capacity of the tested beams. Hii and Al-Mahaidi[5] performed an experimental investigation on torsional behavior of sixmedium scale solid and box-section reinforced concrete beams strengthened with CFRP. Increases in both cracking and ultimate strengths of up to 40 and 78%, respectively, were recorded compared to the base specimens. Ameli et al.[6] presented an experimental investigation on reinforced concrete beams subjected to torsion that are strengthened with FRP wraps in a variety of configurations. The behavior of strengthened beams demonstrated that whereas CFRP strengthened beams failed almost immediately after reaching the peak, the GFRP post peak response took some time to occur. This suggests that GFRP may be a better choice for earthquake strengthening scenarios by providing better energy absorption. Mohammadizadeh et al. [7] carried out an experimental investigation to evaluate the effect of various steel torsional reinforcement ratios on the torsional behavior of strengthened beams with the same volumetric ratios of CFRP reinforcement. It is found that the increase in CFRP contribution to torsional strength is close for various steel reinforcement ratios, when compared to increasing the total amount of steel reinforcement.

The present study contributes to the extremely limited existing literature on torsional tests of strengthened beams with FRP materials. The recent increase interest for the use of these materials, the catastrophic character of the torsional failure and the lack of relative studies are the main motives behind this effort.

## Experimental Program

Experimental tests were carried out in the laboratory of the Civil Engineering Department of the Mosul University. Five rectangular reinforced concrete beams with dimensions 150 mm×250 mm×2350 mm were cast in two batches. The overall length of the beams was 2350 mm. Test span of beams was measured at 2100 mm. A clear concrete cover to the outer surface of stirrups was 20 mm. Additional torsional reinforcement was placed at both ends of the beam to prevent premature failure in the end zone. The transverse and longitudinal reinforcements were arranged according to the design provisions of Building Code Requirements for Structural Concrete[8]. The specimens were reinforced with four 12 mm diameter longitudinal bars located at four corners of the cross-section. Stirrups of 8 mm diameter were spaced at 100 mm on the center throughout the test region. Rebar and stirrup yield strength were 575MPa and 475MPa respectively. The compressive 28-day strength of concrete was 30.0 MPa. The total steel ratio of longitudinal and transverse reinforcement was 2.033%. Figure (1) shows geometrical details of beams and steel reinforcement provided in the test zone as well as in the end zones. One beam, called B1, was tested without CFRP as reference beam. The remained were then strengthened by a unidirectional woven carbon fiber fabric of type SikaWrap®-30C/45 in different configurations. The technical properties of SikaWrap®-30C/45 as given by the manufacturer are presented in Table 1. Different configurations of CFRP were implemented as shown schematically in Figure (2). As CFRP were wrapped around the beams, their fibers orientation was perpendicular to the longitudinal beam axis. The beam B2 was strengthened in the first scheme (scheme #1) with CFRP sheets in the U-strips form of 100mm width at 200mm c/c and additional continuous CFRP strips of 60mm width parallel to the longitudinal axis of the beam on the three long faces. The Beam B3 was strengthened in the second scheme (scheme #2) in a way similar to beam B2, but B3 was wrapped by full vertical strips around the perimeter of the section. The third strengthening scheme (scheme #3) was used with beam B4. The beam B4 was wrapped on two sides and the bottom of the cross section as a U-jacket (U-wrap) and along the entire length. In the fourth strengthening scheme (scheme #4) the fibers were wrapped around the perimeter of the beam B5 section and along the entire length (fully wrapped).

## Description of Testing Rig

All beams were tested under pure torsion. The test rig is shown in Fig. 3. It is a three-dimensional frame designed to allow application of torsion, bending moment and shear force. The beam was simply supported by a roller at each support to avoid any axial restraints. Torsion was applied by means of torsion arm fixed to each end of the beam. The torsion arm was made of **I**-steel sections. The net torsion lever arm was 810 mm. At each load point a hydraulic jack, a load cell, and a spherical support system were installed.

This support and loading arrangement allowed full rotation about the center line of the beam soffit and displacement in the beam axial direction. The jack was operated using a hydraulic pump and the load cell was connected to a data logger for recording the applied load.

The twist angle of the beam was calculated from the displacements of the end cross-section measured by linear variable displacement transformers (LVDT). Strain in the CFRP was measured by means of electrical resistance strain gauges connected to a linear voltage processing data logger.

## Results and Discussions

### *Unstrengthened Beam Behavior*

Figure (4) shows the reference beam torque-twist behavior. The diagonal cracks first appeared at the middle of the vertical faces with an applied cracking torque equal to 4.0 kN.m. The cracks then propagated into the horizontal faces in a spiral form. An examination of the torque-twist curve reveals that the beam behave sensibly elastically before initial cracking. The cracks gradually widened at the middle test span as load increased with the two beam segments rotating relative to one another about the horizontal axis where spalling and crushing of concrete took place just prior to failure (Figure 5). The beam reached an ultimate torque of 8.36 kN.m and exhibited a ductile behavior due to the amount of reinforcement provided, which is greater than the minimum reinforcement required to avoid the failure of beam at cracking [10].

***Strengthened Beam Behavior***

The torque-twist behavior of beam B2 in comparison with the reference beam B1 is shown in Figure (6). The initial cracking torque was 4.22 kN.m, while the ultimate torque was 10.05 kN.m with an increase of about 19% with respect to B1. Strengthened beam B2 showed initial cracks at approximately the same torque as the unstrengthened beam B1. However, the presence of CFRP strips prevented the cracks from widening and propagating on the vertical face. One of these cracks widened as the failure load approached and finally failure took place with debonding of the CFRP strips at its free edge. The failure pattern when closely examined (Figure 7) reveals that failure is possibly due to flexure in a skewed plane where the spalling of concrete did not occur.

From Figure(8) it can be seen that using full vertical strips around the perimeter of the section has caused a significant increase in the ultimate torque. Cracking torque of beam B3 was 5.0kN.m. This result proves that the retrofit material begins working only after sufficient cracking occurred in the member. The beam failed at an ultimate torque of 12.32kN.m with an increase of about 47% compared to unstrengthened beam B1. Excessive concrete crushing followed by CFRP rupture close to mid-span controlled the failure of beam B3 (Figure 9). One interesting point was observed during the test and is exhibited in the Figure (8), which is, that the beam failed suddenly after reaching its peak torque.

The behavior of B4 to the ultimate strength is similar to beam B2 and sustains ultimate torque very close to that of B2 (Fig. 10).During loading, the cracks created on the top face of the beam (where it is not wrapped by CFRP) are gradually opened in a skewed form and finally failure took place with debonding of the CFRP jacket at free edges (Fig. 11) and ultimate torsion equal to 10.63 kN.m. The reason for the deficiency strengthened beams B2 and B4, using U-strips or U-wrap, is that the CFRP free edges were not provided with anchorages.

Figure (12) shows that the fully wrapped of the torsion region of a reinforced concrete beam is more effective in increasing the torsional strength of the beam B5, compared to beams strengthened by other schemes. The initial cracking torque as observed from torque-twist behavior in Figure (12) appears to be 5.0 kN.m. Using the CFRP full wrapping, the ultimate torsion increased 73% more than the reference beam B1. The fully wrapped CFRP strengthening confined the concrete which improved the concrete strength, prevented the cracks from widening, delayed the failure and finally resulted in a significant increase in the ultimate deformation. Beam B5 failed at an ultimate torque value of 14.44 kN.m with excessive concrete crushing followed by CFRP rupture at mid-span, as shown in Figure (13).

Table 2 provides a summary of ultimate torques of all test beams together with their relative percentage increase in ultimate torques in comparison with the reference beam and failure modes.

### *Strain in CFRP*

The CFRP strains, in transverse and longitudinal direction, along the principal fiber direction on the middle test span were measured. Fig. 14 shows the experimental results in terms oftorque versus CFRP strain in transverse direction. The strain does not vary until cracking occurs, widens and propagates. By qualitative study of Fig. 14, it can be seen that CFRP strain levels corresponding to beams **B2** and **B4** less than those of the beams **B3** and **B5**. These differences are attributed to beams failure modes. The failure of beams **B3** and **B5** is mainly characterized by fiber rupture, whereas beams **B2** and **B4** exhibited premature debonding. The strain of the fibers could be used as an index for the effectiveness of the FRP fabrics, since it represents a rate of fibers utilization in beams strengthening.

Torque versus CFRP strain in longitudinal direction is shown in Fig. 15. The maximum value of the CFRP strain indicates that the longitudinal strips had a marginal effect on the torsional strength of the beams.

## Conclusions

The results of this research can be summarized as follows:

i. Employing externally bonded CFRP sheets resulted in an increase in ultimate strength. The amount of increases in ultimate torsional strength was mainly dependent on the strengthening configuration. Moreover, retrofitting changes the mode of failure of the beams.

ii. Experimental results showed that the retrofit material begins working only after sufficient cracking occurred in the member.

iii. Although U-jacket (or U-strips) are easy to apply and fits various torsional strength applications, it was found to be the less effective relative to the fully-wrapped and full strips. The full wrapping was found to be the most effective strengthening scheme. However, it is not likely to be applied successfully in all practical cases due to the lack of access to all sides of the beam for wrapping. Although the U-jacket or U-strips strengthening scheme was less effective than the full wrapping, its efficiency can be enhanced by providing it with a sufficient anchorage system.

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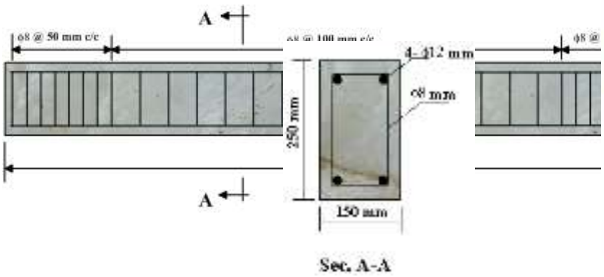
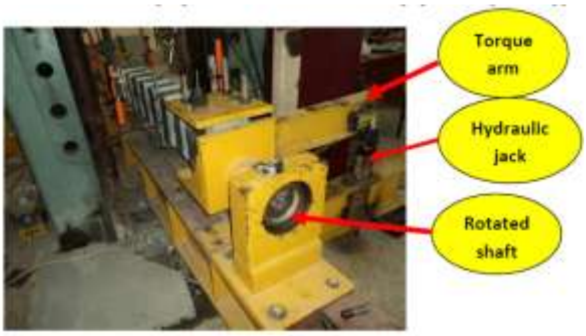
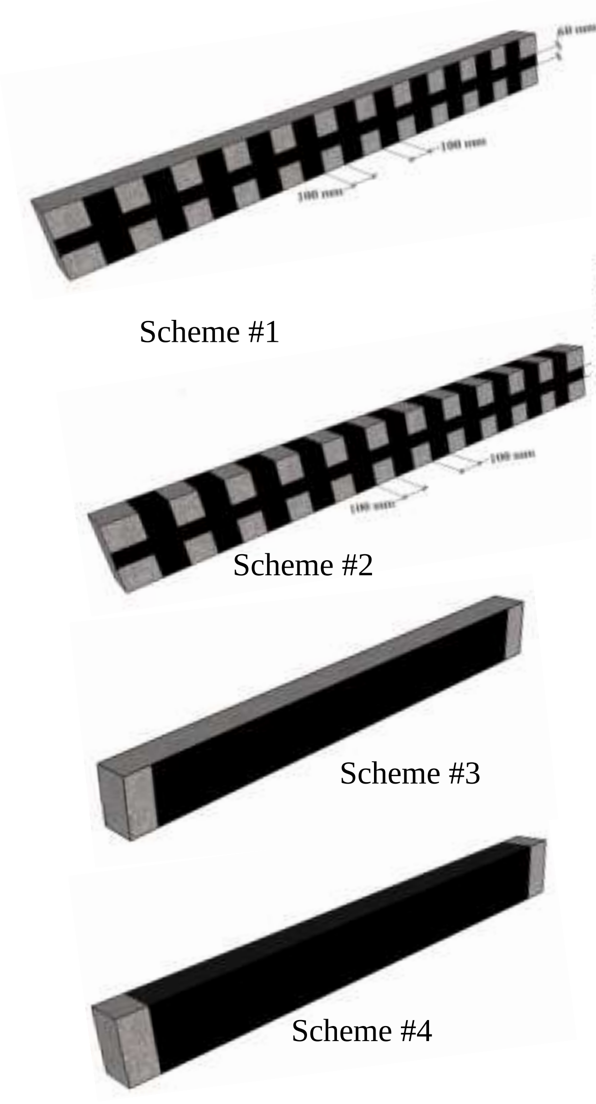


Figure(1) Reinforcement details of the test beams.



Figure(3)Test rig with a typical beam installation.



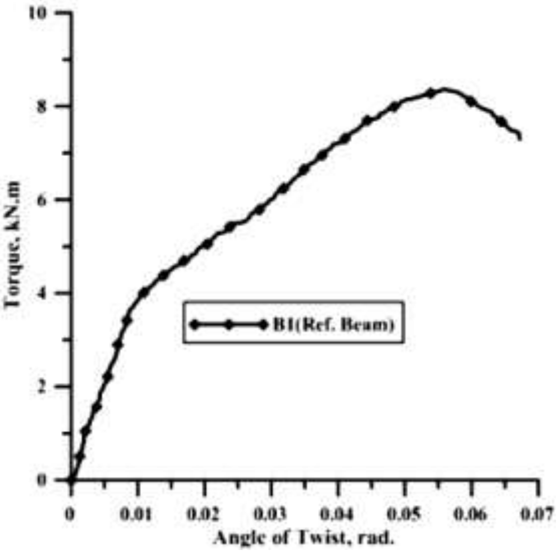
Scheme #1

Scheme #2

Scheme #3

Scheme #4

Figure(2). Strengthening schemes.



Figure(4):Torque-twist behavior for the unstrengthened beam B1.

Figure(5)Crack pattern at failure for unstrengthened beam B1.

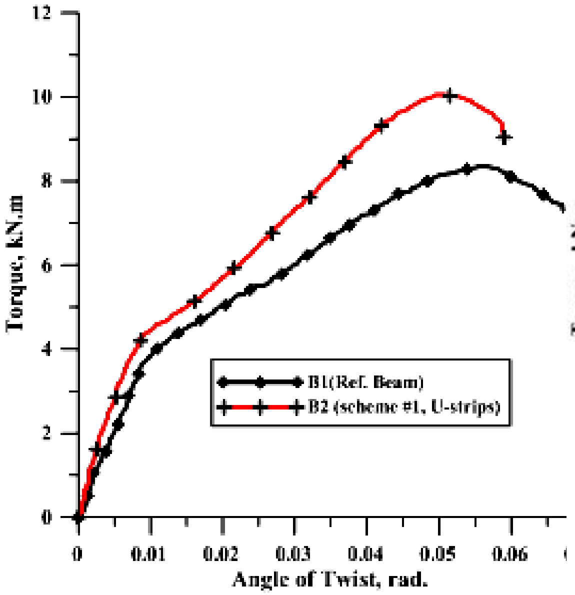


Figure (6) Torque-twist behavior for beams B1 and B2.

Figure(7)Crack pattern at failure for beam B2.

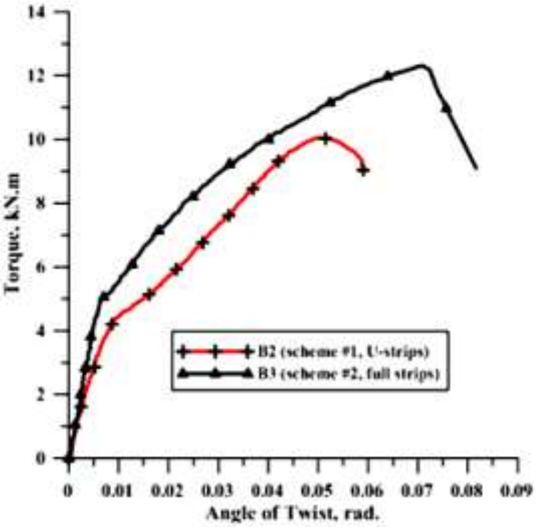


Figure (8)Torque-twist behavior: Effect of full strips over U-strips.

Figure (9)Crack pattern at failure for beam B3.

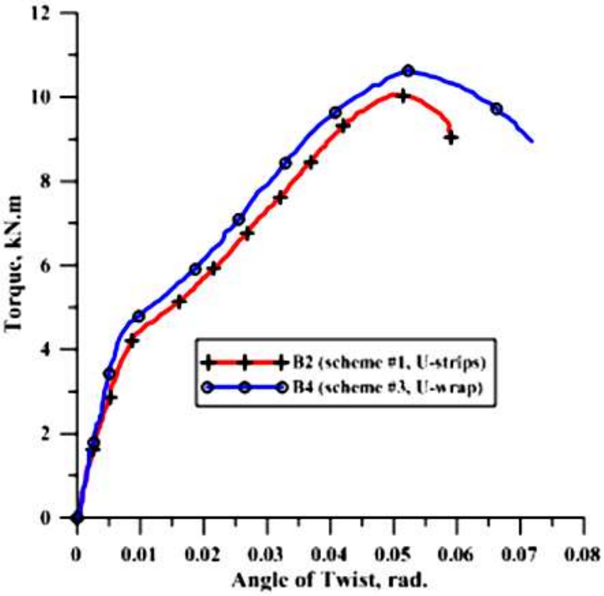


Figure (10) Torque-twist behavior Effect of U-wrap over U-strips.

Figure (11). Crack pattern at failure for beam B4.

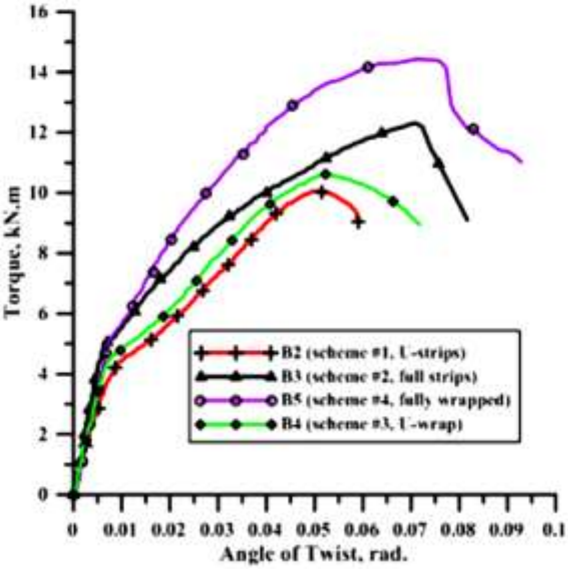


Figure (12).Torque-twist behavior: Effect of fully-wrapped over other schemes.

Figure (13)Crack pattern at failure for beam B5.

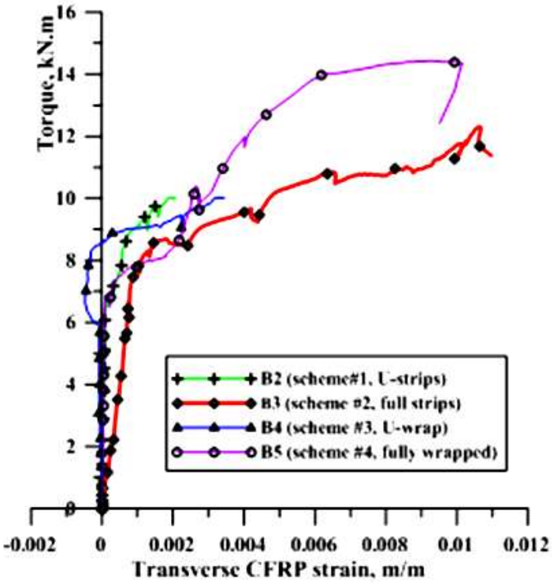


Figure (14) Torque versus CFRP strain in transverse direction.

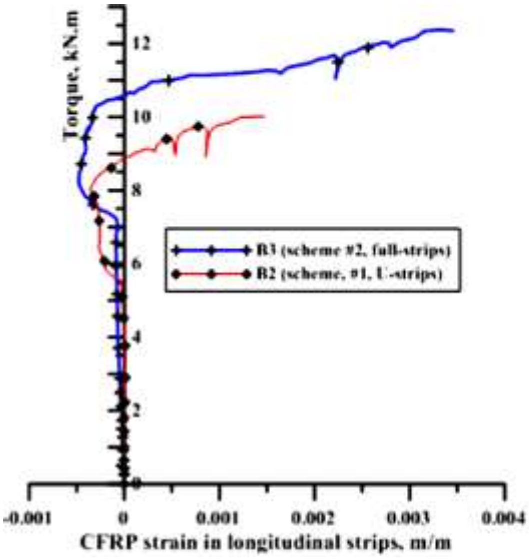


Figure (15) Torque versus CFRP strain in longitudinal direction.

## Table (1)
## Properties of SikaWrap®-30C/45 [9].

| | |
|---|---|
| **Tensile strength (MPa)** | 4300 (nominal) |
| **Tensile E-modulus (MPa)** | 234000 |
| **Elongation at break (%)** | 1.8 |
| **Fabric width (mm)** | 600 |
| **Fabric Thickness (mm)** | 0.131 |

## Table (2)
## Ultimate Torques and Corresponding Increase Percentage and Failure Modes.

| **Beam No.** | **Ultimate Torque (kN.m)** | **Ultimate Torque increasing (%)** | **Failure Mode** |
|---|---|---|---|
| B1 (Ref. beam) | 8.36 | ------------------- | Yield & Crushing |
| B2 | 10.05 | 20 | Diagonal cracking & CFRP Debonding |
| B3 | 12.32 | 47 | Crushing & CFRP Rupture |
| B4 | 10.63 | 27 | Diagonal cracking & CFRP Debonding |
| B5 | 14.44 | 73 | Crushing & CFRP Rupture |