Research on Engineering Structures & Materials
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Research Article

Torsional behavior of concrete-filled cold-formed steel beams with box-shaped webs

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Article Info

Article History:

Received 03 June 2025

Accepted 01 Aug 2025

Keywords:

Cold-formed steel beams;
Torsional moment;
Angle of twist ;
Box web beams;
Concrete

Abstract

This study aims to evaluate the torsional performance of cold-formed steel beams with concrete-filled box webs (BWCFSB) under concentrated torsional loading. The primary objective was to investigate the effect of varying width-to-depth (W/D) ratios and the inclusion of concrete infill on the torsional strength, stiffness, and deformation characteristics of the beams. An experimental program was conducted involving four full-scale beam specimens, each subjected two equal concentrated torsional loads applied symmetrically at equal distances from the supports. All specimens shared consistent dimensions, including a 1500 mm clear span, 3 mm web and flange thickness, and a constant beam depth of 190 mm. The beam width was varied to achieve W/D ratios of 1.15, 1.0, 0.85, and 0.7. Bolted connections between the webs and flanges were spaced at L/6, and each beam was reinforced with eight stiffeners located under the load and support points on both sides. Concrete infill was used to enhance the torsional rigidity of the box webs. Test results indicated that the beam with W/D ratio of 1.15 and concrete infill (P1.15) achieved the highest ultimate torsional moment capacity among all specimens. Specifically, the P1.15 beam surpassed the torsional capacities of the P1.0 (control), P0.85, and P0.7 beams by 19.58%, 108.42%, and 181.23%, respectively. Additionally, the P1.15 beam exhibited superior resistance to angle of twist, with corresponding reductions of 8.93%, 46.68%, and 105.34%. Increasing the box web area through a higher W/D ratio and incorporating concrete infill markedly enhances the torsional resistance and rotational control of cold-formed steel beams.

1. Introduction

Steel shaped by cold forming offers several advantages, including very light weight, compatibility with standard joining methods, dimensional accuracy, manufacturing versatility, ease of handling and transportation, and cost-effectiveness [1,2]. It is widely used in the construction industry, as well as in railroad carriages and vehicle body manufacturing. CFS sections are produced by shaping flat steel sheets, plates, or strips using roll forming or press brakes. Typically, cold-formed steel structural elements have Thicknesses varying between 0.5 mm and 6 mm. Compared to hot-rolled steel, cold-formed components are lighter and more economical. Common shapes for CFS sections include C-channels, Z-sections, and I-sections. However, due to their thin walls, these sections often experience complex buckling behaviors, prompting the development of modern CFS designs featuring hollow tubes and reinforced flanges. These newer configurations combine the high strength-to-weight ratio of traditional CFS with the robustness of hot-rolled steel [3].

Recent research has examined the performance of cold-formed hollow steel sections. conducted experiments to compare cold-formed hollow steel sections with those that are hot-rolled, looking at how the way they are made affects their material properties and how well they perform

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DOI: http://dx.doi.org/10.17515/resm2025-945me0603rs

structurally. While both section types displayed similar geometric imperfections, Cold-formed sections exhibited considerable residual stresses as a result of the bending process used during their fabrication. Additionally, the corners of these cold-formed sections exhibited enhanced strength [4]. explored the shear behavior of concrete-filled box web cold-formed steel beams, as illustrated in Fig. 1. They conducted twenty-four shear tests on simply supported RHFCB specimens, loading them until failure. The inclusion of concrete within the rectangular hollow box webs enhanced both the torsional buckling resistance and the twisting angle strength of the beams, thereby strengthening the web region [5].

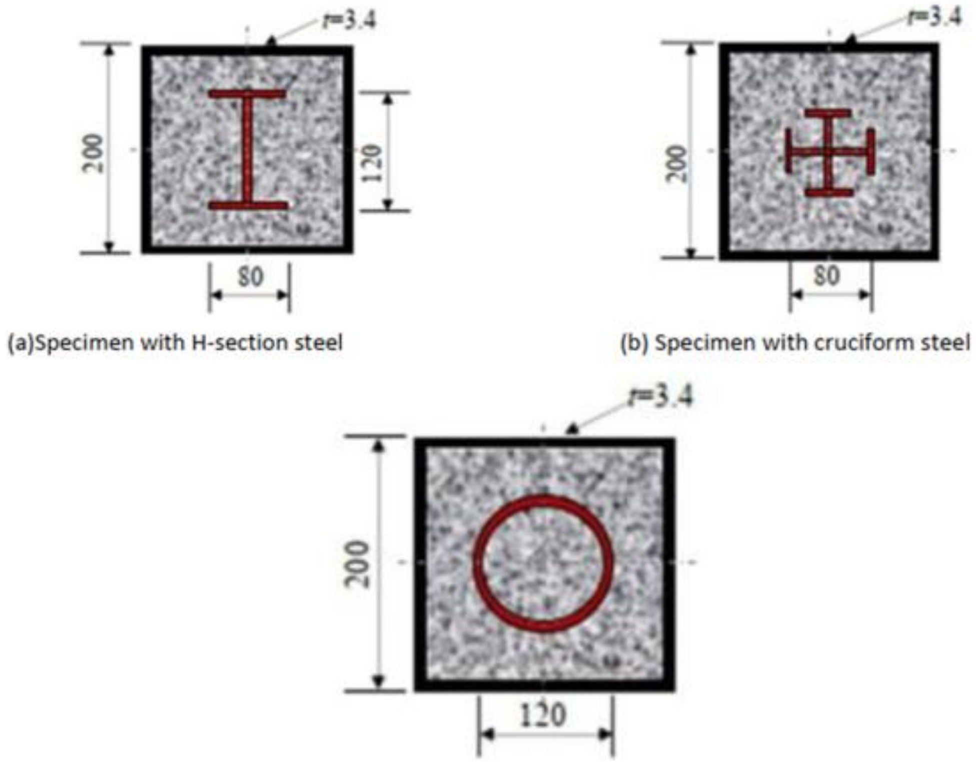

Fig. 1. Box web cold-formed steel beams filled with concrete [5]

A study investigated the torsional behavior of concrete-filled pentagonal box beams (CFPFB) under combined torsional loading using both experimental analysis and finite element (FE) simulations. The research focused on understanding the failure modes, torsional strength, and the impact of a transverse stiffener on the beam's performance. Their numerical model demonstrated a deviation of less than 10% in predicting torsional capacity [6]. In a separate study, proposed both theoretical and numerical design formulas for assessing the buckling resistance of an innovative high-strength concrete-filled tubular web beam (HS-CFTFB) [7]. Their experimental and numerical work on the lateral-torsional buckling (LTB) response of HS-CFTFBs revealed that concrete infill plays a significant role in preventing web deformation [8]. Researchers have studied how web distortion affects the torsional capacity of Triangular Hollow Web Beams (THWBs) under combined torsion. They found that this distortion significantly impacts the torsional capacity, particularly in members with slender webs or when the smaller flange is in compression. To account for this effect, they introduced a simplified formula for the distortion factor, which represents the reduction in torsional capacity due to web distortion. This formula is useful for designing Hollow Flange Beams (HFBs) that are susceptible to lateral-distortional buckling [9]. Additionally, assessed the torsional Performance of cold-formed rectangular hollow web girders (RHWGs) through a combination of experimental testing and numerical modeling [10]. The investigation into the buckling behavior of rectangular web-flanged girders (RWFGs) revealed that web distortion becomes particularly significant in medium- to long-span structures. This means that as the length of the girder increases, the tendency for the web to deform out-of-plane (distort) becomes more pronounced, affecting the overall stability and load-carrying capacity of the girder [11,12]. Moreover, the moment-gradient factor of rectangular hollow web girders

(RHWGs) was found to be influenced by both the thickness of the web and the count of sides [13]. In their study of concrete-filled tubular flange girders (CFTFGs), showed that web distortion can significantly reduce torsional capacity, even when minimal stiffening is present[14]. evaluated the sectional moment capacity of RHWGs using two-point loading experiments and numerical simulations discovered web distortion was readily apparent in constructions with medium to high span widths. Additionally, they revealed that the moment gradient factor of RHFGs was personalized by the web's thickness and number of sides [15, 16]. Their findings revealed that existing design standards significantly underestimate the moment capacity of tubular flange beams (TFBs), and that the tubular web plays a critical role in their buckling performance. Additionally, in their research on bolted connections in built-up I-shaped columns formed from back-to-back lipped channels, observed that increasing the longitudinal bolt spacing beyond half the span markedly reduced load-bearing capacity [17,18]. Finite element modeling has shown that removing openings from the web of a steel beam significantly increases its maximum torsional load capacity. This is because web openings disrupt the stress flow within the beam, particularly under torsional loads, and introduce stress concentrations around the opening's edges. By eliminating these openings, the beam can better distribute torsional forces and resist twisting, thus enhancing its overall torsional strength. These results align with findings from Gunasekaran et al. and Zhang et al., who highlighted the beneficial effects of concrete infill in improving structural torsional resistance. However, this study extends the existing literature by systematically quantifying the effect of varying W/D ratios in cold-formed configurations, which is not extensively addressed in previous work [19, 20,21].

2. Testing Program

Sections made from cold-formed steel (CFS) are widely utilized to counteract web buckling under torsional loading. This study examined the combined torsional behavior of a series of cold-formed steel beams featuring box-shaped webs, each differing in concrete-filled web areas and width-to-depth (W/D) aspect ratios. The investigation centered on the role of the box web in affecting torsional performance, rotation angle, resistance enhancement under combined torsion and bending, reduction in deflection, and comparative performance across the specimens. An overview of the test specimens is presented in Table 1, while Table 2 presents the four particular beam samples examined in this study.

Table 1. The description of specimens

Specimen Identification	Description
P(1.15)	CFS beam with box web filled with concrete have width to depth (W/D=1.15)
P(1) control specimen	CFS beam with box web filled with concrete have width to depth (W/D=1)
P(0.85)	CFS beam with box web filled with concrete have width to depth (W/D=0.85)
P(0.7)	CFS beam with box web filled with concrete have width to depth (W/D=0.7)

Table 2. Information of the test steel beams

Beam symbol	No of stiffener (S)	L mm	D mm	W mm	t mm	W/ D	As mm^2	Ac Mm^2
P(1.15)	4	1500	190	222	3	1.15	5052	25024
P(1) control specimen	4	1500	190	190	3	1	4860	19136
P(0.85)	4	1500	190	165	3	0.85	4710	14536
P(0.7)	4	1500	190	136	3	0.7	4536	9200

3. Technical Section Details

The experimental investigation focused on sections with varying hollow web areas and different width-to-depth (W/D) ratios. It examined two primary Features of four different types of concrete-filled Steel shaped by cold forming box beams featuring hollow webs. The I-section dimensions were based on section specifications, including parameters such as overall depth and thickness, and were in accordance with IS 811-1987: Code of Practice for Design and Use of Cold-formed Light Gauge Structural Steel Sections. Each beam had a uniform thickness of 3 mm, while flange widths differed across specimens (222 mm, 190 mm, 165 mm, and 136 mm). The web depth was kept constant at 190 mm, and all specimens had an overall span length of 1500 mm. Figure 2 illustrates the detailed specifications of the beams tested.

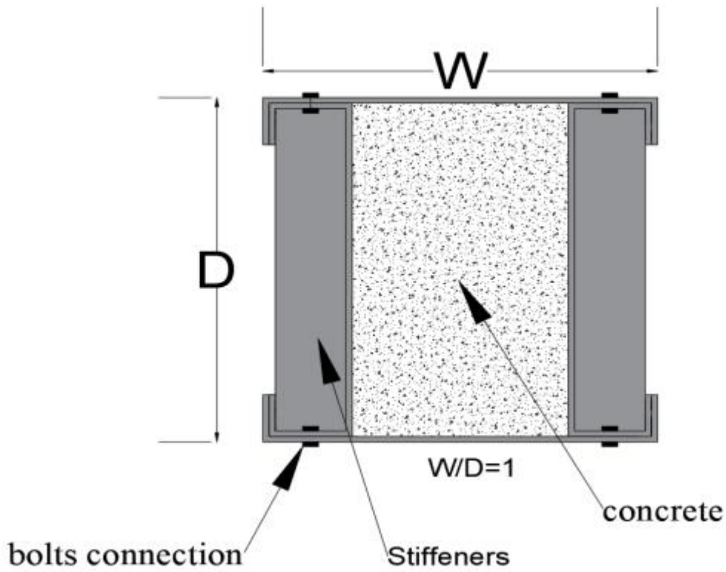

Fig. 2. Specimens' details

4. Investigation and Progress

4.1. Experimental Specimens

Cold-formed steel is a category of steel that is made, refined and extracted at room temperature by grinding, the manufacture process of cold-formed steel products will be carried out at room temperatures, and pressing and rolling are used in the manufacturing process the steel plates having Yield stress (225MPa), Ultimate strength (295MPa) and thickness of 3 mm were cold-formed at ambient temperature and shaped into I-sections featuring concrete-filled, box-shaped webs. Among the commonly used techniques for forming such sections-cold roll forming and press braking-this study utilized the process of cold roll forming process to produce the I-sections with box webs. A steel sheet of the required length and 3 mm thickness was bent into four individual channel sections Manufactured with a press brake machine, these channels were then assembled and fastened together to create a hollow box-shaped web, as depicted in Fig. 3. This approach enabled the fabrication of a cold-formed steel I-beam with a hollow box web through bolted connections.

Normal weight concrete has Compressive Strength 36MPa was used to fill box web. The box web cast after 28 days from beams casting. Mixing of concrete was performed according to ASTM C192/C192M [22]. The mold was removed after 24 hours of the casting, and then burlap sacks were placed and kept wet through 28 days,

Fig. 3. Constructed test samples

4.1.1 Cement

Sulphate resisting cement (type KAR) was the type of cement used in this research, respect that satisfied (IQS No. 5/1984) limitations [23].

4.1.2 Fine Aggregate

Natural local sand conforms according to the limits of Iraq specification (IQS No.45 /1984) and Consultative Reference Guide (No.500/1994) Weighted Method. Zone (2).[24]

4.1.3 Coarse Aggregate

Natural crashed gravel with a maximum size of (19) mm is used as the coarse aggregate. Mechanical and chemical properties were accepted according to the requirements of (IQS No.45 /1984) and Consultative Reference Guide (No.500/1994) Weighted Method.[24]

4.1.4 Admixture

Flocrete (SP90S) High range water reducing admixture with workability retention properties complies with ASTM C494, Type B, D and G, depending on the dose.1

4.2. Load Application Condition

To apply the load, combined torsional forces were placed evenly between the supports of the beam. Four key points were designated along the span-two located at the supports and two at the points where the torsional loads were applied. This configuration enabled the beam to twist in four separate directions and Is referred to as the torsional-point method. As shown in In Fig. 4, the distance between the torsional load arms was (500 mm), while the total span between the supports measured 1500 mm. The two arm-applied point loads created a consistent torsional moment without introducing any shear force between the loading points, thereby establishing a combined torsional loading condition.

4.3. Support Arrangements

The combined torsion method was employed to construct a concrete-filled cold-formed steel I-beam featuring a hollow box-shaped web, assembled using bolts. As illustrated in Fig. 4, the beam was simply supported, incorporating a roller support at one end and a pinned support at the other. Each beam had a uniform span of 1500 mm, with the supports placed 100 mm inward from both ends [25,26].

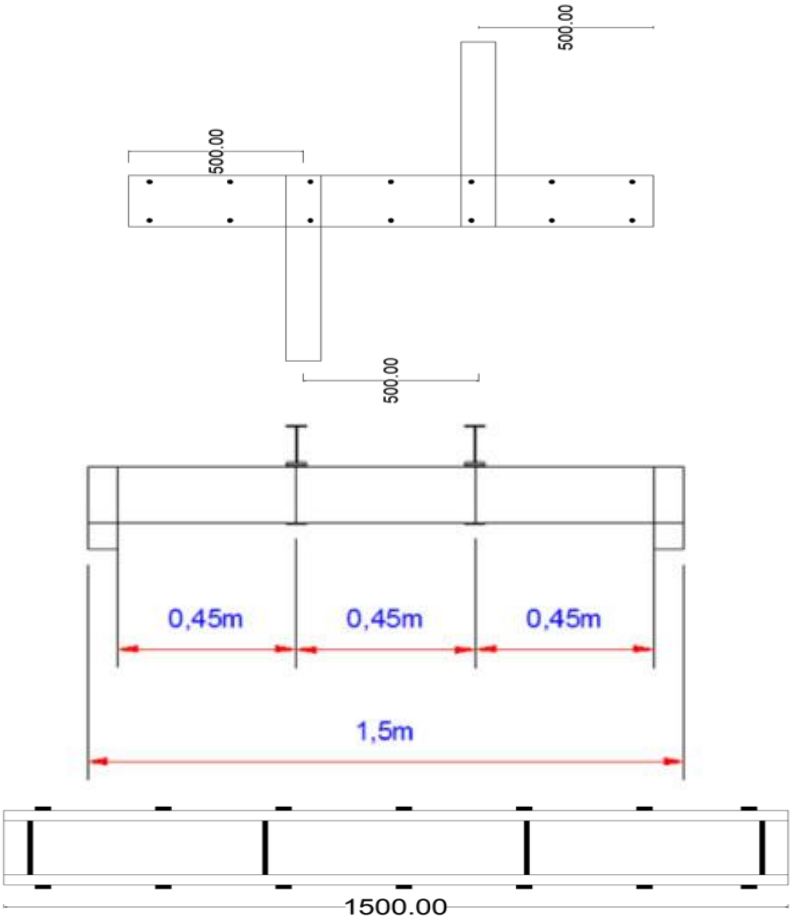

Fig. 4. Details of box web cold-formed steel beams and Number of stiffeners and the distances between them

4.4 Boundary Conditions

The limiting criterion denotes a standardized scale or value employed for comparison. performance of different sections on a common basis. In this study, the torsional ultimate capacities of the sections were evaluated using the angle of twist as the standard measurement. According to BS 5950-5:1998, Standard Practice for Engineering Cold-Formed Thin-Walled Steel Sections, the allowable rotation limit is defined as span/300.

5. Experimental Results and Evaluation

Combined torsional loading tests were performed on four different specimen types using a universal testing machine with a 600 kN capacity and adjustable supports tailored to the required span. Load application and corresponding rotational data were Measured, documented, and extrapolated when required. The deformation of the specimen was tracked using LVDT sensors. One LVDT was installed at the center of the bottom flange to monitor vertical deflection, while another was placed beneath the loading arm to measure rotational movement, as depicted in Fig. 5. An additional sensor was positioned directly beneath the point of load application at the bottom of the beam to monitor localized displacement. As the load was progressively applied using a hydraulic jack, the cold-formed steel beam began to twist, and local buckling was observed in the web area directly below the applied load.

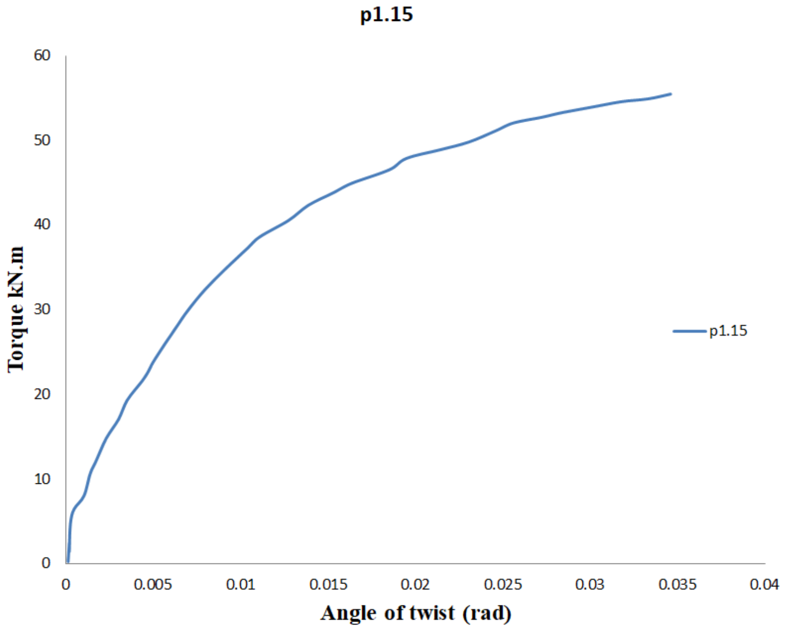

Fig. 7. Torque rotation curve for beam (p1.15)

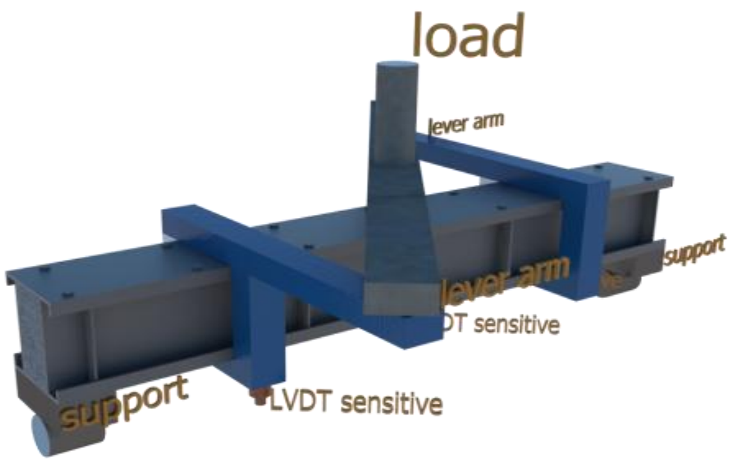

Fig. 5. Location of LVDT sensors

5.1. Beam P(1.15) with Box Web Filled With Concrete

This beam consisted of box web filled with concrete. The depth of beam was 190 mm and width 222 mm the ratio between width to depth (W/D=1.15). The beam consists of four part this part connected with bolts to make box web cold-formed steel beam, and the span length measured 1500 mm. The specimen p(1.15) section was capable of supporting a maximum torsional moment of 55.463 kN·m, with the corresponding angle of twist being 0.0345 radians.

Fig. 6. Laboratory testing and failure of P(1.15)

5.2. Beam P (1) Control Specimen with Box Web Filled With Concrete

This beam (control specimen) consisted of box web filled with concrete. The depth of beam was 190 mm and width 190 mm the ratio between width to depth (W/D=1). The beam consists of four part this part connected with bolts to make box web cold-formed steel beam, and the span length measured 1500 mm. The specimen p(1) control specimen section was capable of supporting a maximum torsional moment of 46.3796 kN·m, with the corresponding angle of twist being 0.0376851 radians.

Fig 8. Laboratory testing and failure of P(1) control specimen

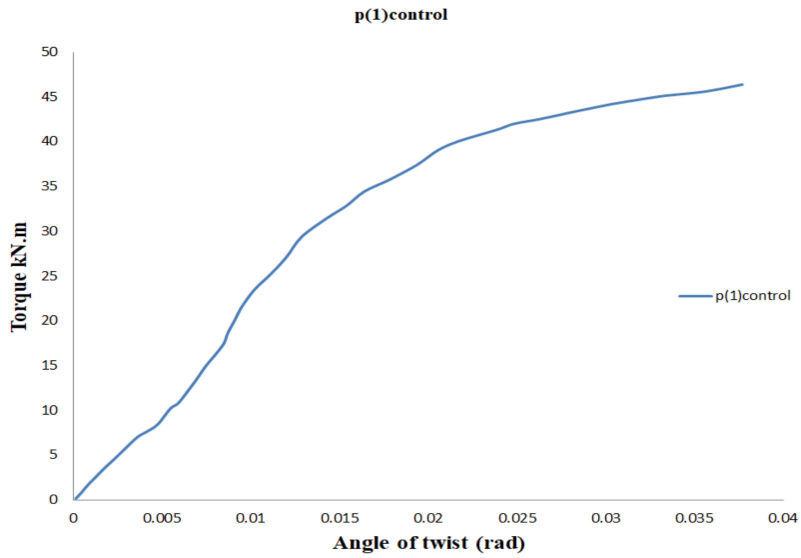

Fig. 9. Torque rotation curve for beam (p1) control specimen

5.3. Beam P(0.85) with Box Web Filled With Concrete

This beam consisted of box web filled with concrete. The depth of beam was 190 mm and width 165 mm the ratio between width to depth (W/D=0.85). The beam consists of four part this part connected with bolts to make box web cold-formed steel beam, and the span length measured 1500 mm. The specimen p(0.85) section was capable of supporting a maximum torsional moment of 26.61kN·m, with the corresponding angle of twist being 0.0202 radians.

Fig. 10. Laboratory testing and failure of P(0.85)

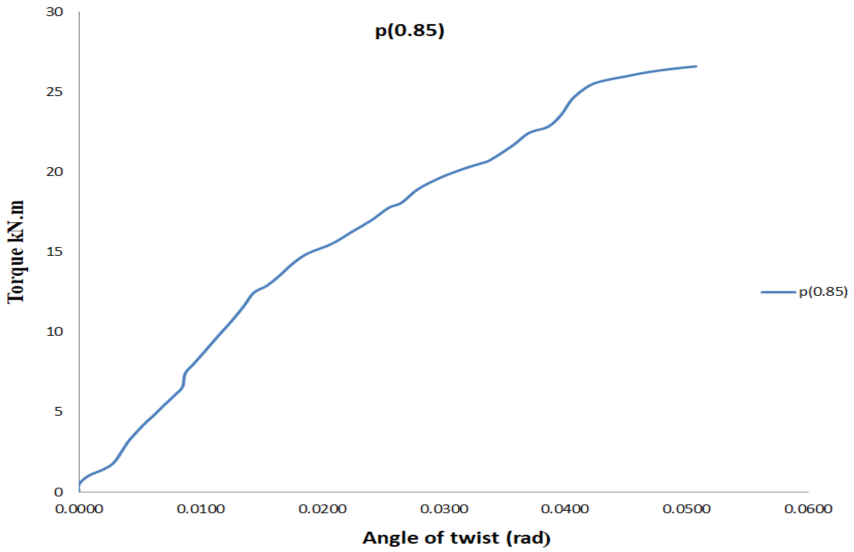

Fig. 11. Torque rotation curve for beam (p0.85)

5.4. Beam P(0.7) with Box Web Filled With Concrete

This beam consisted of box web filled with concrete. The depth of beam was 190 mm and width 136 mm the ratio between width to depth (W/D=0.7). The beam consists of four part this part connected with bolts to make box web cold-formed steel beam, and the span length measured 1500 mm.

Fig. 12. Laboratory testing and failure of P(0.7)

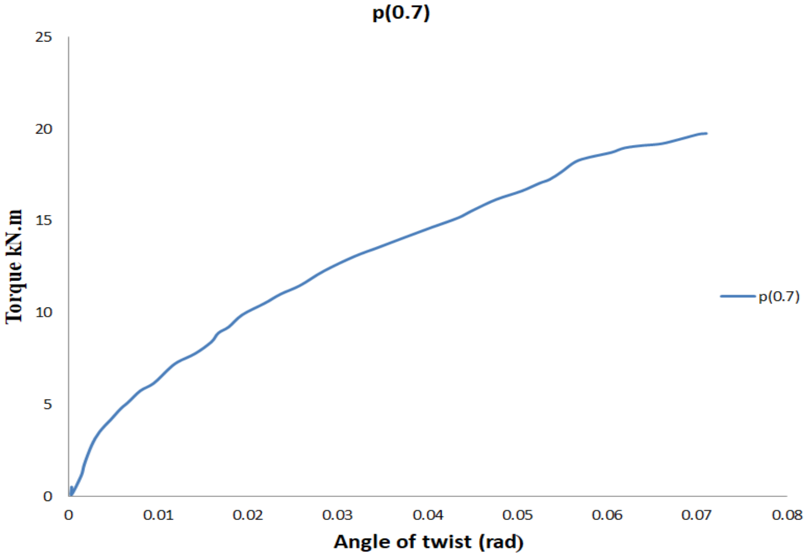

Fig. 13. Torque rotation curve for beam (p0.7)

The specimen p(0.7) section was capable of supporting a maximum torsional moment of 19.76631kN·m, with the corresponding angle of twist being 0.0710309 radians.

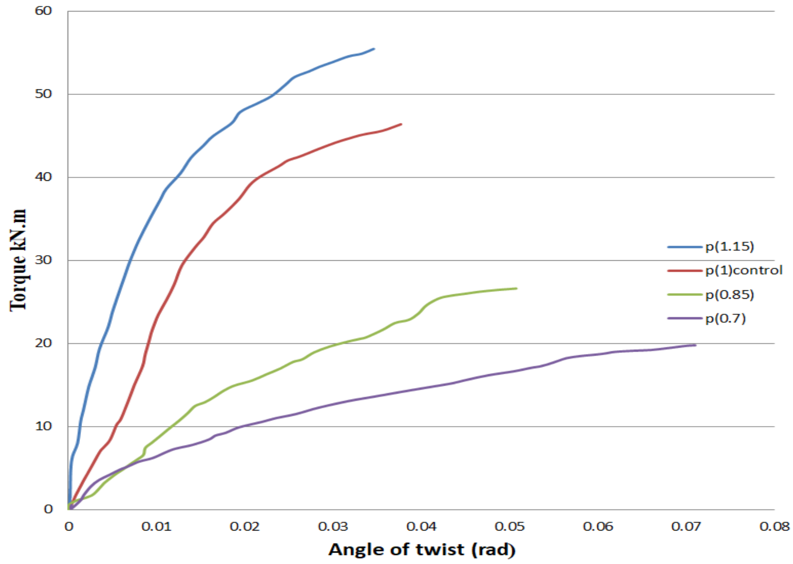

Fig. 14. Torque rotation curve for all beam

6. Analysis

The experiments were conducted, and results were recorded. The components were made from mild steel, with a yield stress of 266.1 MPa and a Young's modulus of 200,000 MPa. Following the Code of Practice for the Design of Cold-Formed Thin-Walled Sections (BS 5950-5:1998), the maximum allowable deflection was limited to 5 mm (equivalent to span/300). Table 4 summarizes the results for the four proposed section types. The performance of each section was evaluated using the load-to-weight ratio, which reflects the amount of self-weight required to achieve an increase in torsional capacity and twist angle. A higher ratio indicates superior section efficiency.

Table 3. Results of the Tests on the Designed Specimens

Section type	Ultimate Torsional moment (kN.m)	Angle of twist (rad)	Ductility	stiffness ratio kN/mm	modulus of toughness MPa*10
P(1.15)	55.463	0.03459	2.88	1603.4	1.42042
P(1) control specimen	46.3796	0.03768	1.983	1230.8	1.18290
P(0.85)	26.61	0.05074	1.637	524.43	0.85591
P(0.7)	19.7663	0.07103	1.91	278.28	0.91648

Based on the ratio of ultimate torsional moment to angle of twist, the P(1.15) beam—constructed from cold-formed steel with box-shaped webs, a wall thickness of 3 mm, and a width-to-depth ratio of P(1.15) demonstrated greater efficiency compared to the other specimens, each featuring varying concrete-filled web areas The implications for future design are substantial. Cold-formed steel members with optimized W/D ratios and concrete-filled webs offer enhanced torsional stability, making them ideal for structural applications with high torsional demands — such as open-floor modular buildings, pedestrian bridges, cantilevered balconies, rooftop mechanical supports, and prefabricated structural frames. This approach enables lighter steel members to meet higher performance standards without increasing section size or weight.

7. Conclusion

This study examined the torsional performance of cold-formed beams featuring box-shaped web sections. The key conclusions from the research are as follows:

- In designing cold-formed steel (CFS) box web sections, it is crucial to Include both web buckling and the aspect ratio of the web in the analysis. The beam's ultimate torsional capacity is greatly affected not only by its thickness and width-to-depth (W/D) ratio but also by its yield strength.
- A cold-formed steel (CFS) beam with a concrete-filled box web and a width-to-depth ratio of 1.15 (W/D = 1.15) demonstrated the highest capacity to resist ultimate torsional moment, reaching 55.463 kN·m. This performance was 19.58% greater than the P(1) control specimen, 108.42% higher than the P(0.85) beam, and 181.23% greater than the P(0.7) beam. The increased W/D ratio led to a larger box web area, which in turn enhanced the torsional moment resistance and reduced the angle of twist. Consequently, the web became more rigid and was able to withstand greater loads.
- The results showed that increasing the width-to-depth ratio enhanced the size of the concrete-filled box web, which in turn improved the beam's ultimate torsional capacity, reduced its angle of twist, and increased its resistance to buckling. As a result, the larger box web of the P(1.15) beam proved to be more effective in resisting torsion. Overall, the P(1.15) specimen outperformed the other sections as a torsional member while also offering a more cost-effective solution.
- the maximum angle of twist for the P(1.15) beam was reduced by 8.93%, 46.68%, and 105.34% compared to the P(1.0), P(0.85), and P(0.7) beams, respectively. These findings indicate that increasing the box web area significantly improves the torsional resistance and rotation control of the beam

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