Flexural -Torsional Buckling Tests of Cold-Formed Lipped Channel Beams Under Restrained Boundary Conditions

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Abstract

In this paper, tests on flexural buckling (Lateral – Torsional) of cold-formed steel(CFS) lipped Channel beams under restrained boundary conditions are described Two point loading for flexural tests have been established for 3.0m span to obtain uniform bending moment. The section sizes selected for testing are 100x50x10 mm, 100x50x15 mm and 100x50x20 mm with 1.6mm and 2.0mm thickness for the investigation. Carefully designed loading and support systems were used in the tests to apply gravity load through the web of the section and to ensure that simply supported ends were established. The test results are compared in the BS5950:Part 5 and IS code 801-1975. The influence of warping and torsional restraints on flexural capacity is presented. The influence of buckling length for different boundary conditions proposed by Rhodes was considered to calculate critical flexural-torsional buckling moment.

Keywords : - **Cold-Formed Steel, Flexural torsional buckling, Finite element, Slenderness ratio, Boundary conditions and warping restraint.**

I. Introduction

The Major advantage of CFS beams over hot rolled beams is to be found in the relative thinness of the material from which the sections are formed. This will lead to have highly effective in terms of weight and efficient member and structures. However, the promising advantages of the thin walls can only be partially obtained. To obtain these advantages, the designer must be aware of the importance associated with thin-walled members and their effects on analysis and design. The Most important of these phenomena is local buckling.

In thin walled members, the role played by torsion is enhanced in comparison to hot-rolled sections. The reasons for this are listed below

1. Application of load through the shear centre in an open cross-section which has shear centre outside the section is difficult to achieve. Hence, CFS beams are subjected to an applied torque so that twisting of the section is bound to occur if it is not restrained against torsion.
2. The torsion constant J, for open cross sections, which is directly related to the resistance to twist, is proportional to the material thickness raised to the third power.
3. Restraining this torsion induces longitudinal stresses which may be of the same order of magnitude as the primary bending stresses and additive to them.

In most frequent applications, viz, purlins, floor joists and wall studs, the loading and restraint are both continuous, both of which are self-equilibrating to some extent so that the tendency to twist is greatly reduced. Rational methods of analysis in these situations are exceedingly complicated and design usually proceeds on the basis of test results. In this study, continuous restraint is not considered and attention is confined to cases where light gauge steel members are free to twist between discrete points of restraint.

II. Literature Review

Prior to 1980, the in elastic reserve capacity of beams was not included in the AISI specification because most Cold-Formed steel shapes have width to thickness ratios considerably in excess of the limits required by plastic design. In the 1970s, research work on the in elastic strength of Cold-Formed Steel beams was carried out by Reck, (1975) Pekoz, (1980) Winter (1985) and Yener (1985) at Cornell university. These studies showed that the inelastic reserve strength of Cold-Formed steel beams due to partial plasticization of the cross-section and the moment redistribution of statically indeterminate beams can be significant for certain practical shapes. With proper care, this reserve strength can be utilized to achieve more economical design of such members. In addition, the buckling strength and load carrying capacity of continuous of beams and steel decks have also been studied by Wang and Yeh (1974) and Chong and Mosier (1975).

Flexural capacity of discretely braced of ‘C’s and ‘Z’s was studied experimentally by Duane et al. (1992). These studies concluded that quarter point bracing is not needed for channels and Zees not attached to deck (or) sheathing. It was recommended that mid span bracing can be used to control lateral deflection and rotation at service loads. The investigation exhibited “translation rotation failure’. It should be noted that lateral buckling equations in the 1989 AISI specification for predicting the capacity were unconservative for cases where lateral braces are spaced closer than at mid point. Ultimate loads for smaller spacing of braces (A/L = 0.478) to all practical purposes were the same as for continuous bracing reported by Dr Wei Wen Yu.

Strength design curves for thin walled sections undergoing Distortional buckling were developed by Hancock et al. (1994). Two sets of design curves have been proposed and compared with test results. First set is based on an effective section approach and second one provided the prediction of Maximum stress in distortional bucking mode including post buckling reserve capacity of slender sections. Both approaches were found to produce reasonable estimation of results for sections which undergone distortional buckling before (or) at the same time as local buckling.

The behavior of edge stiffened flexural members was investigated by Maria.E. Moreya and Teoman Pekoz (1994). The experimental results showed the same trend as those of Willis and Wallace(2002). The study showed that the smallest lip size was the strongest of all the three specimen tested which was true for all brace conditions. The investigations concluded that this trend may be due to the sharing effects of lip and increase in strength was also observed.

Lateral buckling strength of cold-formed channel beams was investigated by Bogdan et al (1999). The investigation revealed that beams were failed by distortional buckling of most compressed element, quite large deformation developed as in elastic buckling loads were approached. At high half wave lengths, the mode was flexural-torsion buckling and at lower half wave lengths, the mode was lateral distortional buckling. Yield moment of CFS beams under different strain rates was studied experimentally by chi-ling and Wei-Wen Yu (2009). These studies concluded that yield moment of CFS beams increases with increasing strain rates. Experimental studies showed that dynamic yield stress (or) dynamic yield stress-strain relationship can be used in the calculation of yield moment of beams.

Lateral buckling strengths due to moment gradient effects were investigated by Cyrilus and Mahen Mahendran (2009). These studies found that strength benefit of moment gradient for cases with high end moment ratios is unfavorably influenced by Lateral Distortional buckling.

Literature study reveals that the influence of restrained boundary condition on the flexural torsional buckling resistance has not been investigated so far, particularly resistance offered by warping restraints. Various international and national codes, via, AS/NZS 4600, NAS specification, the AISI specification, Euro code and BS 5950,Part 5 have not specified the influence of warping and torsional restrains on the flexural torsional behavior. Some of the provisions appear to be based on intuition without any experimental evidence. Therefore, it is important to obtain test data for restrained CFS lipped Channel beams.

The purpose of this paper is to present a series of flexural tests on CFS lipped channel beams under restrained boundary conditions. In the past, flexural tests of thin-walled lipped channel sections with warping and torsional restraints have not been performed. Therefore, the test strengths of such sections are not known. This paper provides the test strengths of lipped channel beams. All the sections failed in lateral-torsional buckling mode where the flange and lip rotated about the flange-web junction restrained by web.

III. Material Properties

The material properties of each series of specimens were determined by tensile coupon tests. Longitudinal coupons were taken from the centre of the web plate of finished specimens. The coupons were prepared and tested according to Indian standard 1608:-2005 and ISO 6892:1998 for the tensile testing of metals using 20mm wide coupons and gauge length 80mm. The coupons were tested in a 200 KN capacity UTM using friction grips to apply loading. A data acquisition system was used to record the load and the gauge length extensions at regular intervals during the tests. The static load was obtained by pausing the applied straining for one minute near the 0.2% tensile proof stress and the ultimate tensile strength. This allowed the stress relaxation associated with plastic straining to take place. Table I summarizes the material properties determined from the coupon tests. A typical coupon test specimen used in this test program is shown in Fig. 1(a) and 1(b). The stress-strain curve for different thicknesses are shown in Fig. 2.The material properties derived from coupon test are tabulated in Table I.

A. Boundary Conditions

Beams considered for studies are simply supported and its boundary conditions for warping and torsion restraints are tabulated in Table II and shown in Fig. 3. Two 50mm x 100mm size MS plates of 3mm thick are welded, one at each end at side face of the CFS beam to introduce warping restraint fully (WR) and 50mm x

50mm plates are welded to introduce partial warping restraint at ends of the beam at side face either at tension flange (WR (T)),or at compression flange (WR(C)) as shown in Fig.4.

B. Determination of Elastic Lateral Buckling Resistance Moment (M_b)

In BS 5950: Part 5, the rules for determination of the elastic lateral buckling resistance are limited to four specified sections, such as I, C, Z and T beams as shown in Fig.5. These thin elements may buckle locally at a stress level lower than the yield stress of steel when they are subject to compression in flexural bending, axial compression, shear or bearing. The coefficient C_b is used to take account of the variation in moment along a beam. The variation of C_b factor with distribution of moment over the span.

C. Experimental Program : Support System and Loading

In order to investigate the Flexural – Torsional Buckling (Lateral - Torsional buckling) and ultimate strength behavior of CFS lipped channel beams used as flexural members, a full scale bending test rig was designed, fabricated and built in the GCT structural dynamics Engineering Laboratory. The test rig used for lateral distortional buckling tests included a support system and a loading system, in which support system were rigidly fixed in the floor of dynamics laboratory.

Mahendran and Doam (1999) used a loading system with hydraulic jacks. There was a disadvantage of restraining lateral movement of the test beam. It did not allow the continuation of loading into the post buckling range due to the fact that roller bearings could slip out of position and cause injuries to people and damage the components. To eliminate the above mentioned short comings, a new gravity loading system was designed with two rectangular box shaped arrangements suspended from the attachments fixed at 1/3rd points of the test beams attached with chains to accommodate leading discs. It ensured uniform bending moment between the loading points. Zhao et al (1995) and Mahendran and Doam (1999) used the overhang loading method to investigate the lateral buckling of simply supported beams. In this method, the cantilever loads are applied to the test beam at a short distance from the supports. It also provides a uniform bending moment within the entire span. So this method is preferred but it has an undesirable effect of warping restraints due to the overhang component of the test beam. Also it has the limitation on its length due to fabrication difficulties. Hence, longer test beam to accommodate cantilever loads is not suitable in this method and also in this test program. Put et al (1999) used quarter point loading method to investigate the lateral buckling method to investigate the lateral buckling of simply supported beams. This method provides uniform bending moment only between the points of load application. Due to this reason, Overhang loading method was preferred as it provides a uniform bending moment within the entire span, but it has the possible undesirable effect of warping restraints due to the overhang component of the test beam. In addition, it has the limitation on its length due to fabrication difficulties. Hence, longer test beam to accommodate cantilever loads in the overhang method was not suitable in this test program. Therefore two point loading method was adopted as shown in Fig.6(a).

Two Specially designed supports of 1.2m high were fabricated and installed at a spacing of 3 meter in the floor of dynamics Laboratory to support the test beams. The height of the support was fixed in order to provide space for loading platform which will be attached to the beam so that loading will be done incrementally. The two T-shaped torsion restraint plates were fixed by using four bolts at the ends of the beam to provide torsional restraint at support. Fig.7 shows the schematic and overall views of the measuring system.

The detailed test configuration of the flexural tests is shown in Fig.10 for 100mm deep section. The two point bending arrangement provided a central region of uniform bending moment and Zero shear force. The channel section members were loaded symmetrically at two points via two box hanging arrangements. The distance between the two box arrangements was 1000mm. The two box hanging arrangements ensured that the applied loads are vertical. Two dial gauges were used to measure lateral deflection (Out of plane deflection) at mid span and one third span respectively. Two scales were mounted on a separate horizontal beam to measure vertical deflection at mid span and one third span which was placed just above the top of beam. This arrangement is suitable to measure vertical movement of the beam during testing without any disturbance. Rotation of the beam during the tests is recorded by mounting horizontal bar via two vertical plates fixed at the centre of beam. Vertical deflections were measured by affixing a needle at 1/3rd and mid span points which moves on a reference scale. Lateral movements of beam were measured by mounting dial gauges on a stand 1/3rd and mid span respectively. Strain readings were recorded with the help of strain indicator.

D. Test Procedure.

Table III lists the test specimens used in this program while Fig.10(a) shows a typical specimen arrangement for testing. The cross section dimensions and material thicknesses of each test specimen were measured using a vernier caliper and tabulated. The test specimen was placed in a position on Supports and its ends were tied down with 'T' plates which were fixed at beam ends. The loading arms were then bolted to the test specimen at each 1/3rd points. The loading boxes were hanged from the loading arms by of chains. Initial deflections and strains were measured for loading box of weight 400N.Gravity loads of 200N, 100N and 50N were purchased specifically for this test. The beam was tested by applying load at an increment of 200N till the test specimen was failed and corresponding deflections and strains were recorded. The Cross-Sectional rotation of specimen was measured at 1/3rd span and corresponding rotations at mid span were extra-polated. The beam was allowed to deflect and rotate laterally until it was failed by out-of-plane buckling. The buckling behavior of the test beam shown in Fig.12 was observed throughout the test and recorded. Loading pattern was demonstrated in Fig 9 (a) and the pattern of failure was shown in Fig. 10(b).

IV. Results and Discussion

Critical behavior of CFS lipped channel beams under restrained boundary conditions for member length of 3.0 m is presented. It is observed for class A (torsionally restrained) beams from the experimental study that the flexural capacity increases by 11.11% for the increase of lip size from 10mm to 15mm with 1.6mm thickness. It increases by 6.67% for the increase of lip size from 15mm to 20mm with 2.0mm thickness as shown in Fig.11(a) and 11(b). Also, it is observed for class B (warping and torsionally restrained) beams that flexural capacity increases by 5.71% for the increase of lip size from 10mm to 15mm with 1.6mm thickness, 4.55% for the increases lip size from 15mm to 20mm with 2.0mm thickness. Further, it is inferred for class C beams that flexural capacity increases by 9.09% for the increase of lip size from 10mm to 15mm with 1.6mm thickness, and increases by 7.69 % for the increase of lip size from 15mm to 20mm with 2.0mm thickness. Also it is inferred for class D beams that flexural capacity increases by 9.68% for the increase of lip size from 10mm to 15mm with 1.6mm thickness, and increases by 8.82% for the increase of lip size from 15mm to 20mm with 2.0mm thickness. Hence, it is concluded that flexural capacity increases substantially when lip size increases from 10mm to 15mm than from 15mm to 20mm.It is established from the experimental study that warping restraint in addition to torsional restraint increases the flexural capacity by 29.6% for 10mm lip size, 23.33% for 15mm lip size for the CFS beam of 1.6mm thickness. Also, it is found that warping restraint in addition to torsional restraint for 2.0mm thick CFS beam increases the flexural capacity by 46.67% for 15mm lip size and by 43.75% for 20mm lip size. It is determined from the study that warping restraint provided to compression flange in addition to torsional restraint increases the flexural capacity for 1.6mm thick CFS beam by 22.2% for 10mm lip size and 20% for 15mm lip size. Also, it is found that partial restraint to warping in addition to torsional restraint influences the flexural capacity by 44.4% increase for 15mm lip size and 40% increase for 20mm lip size for the same thickness of 2.0mm. Further, It is observed that warping restraint to tension flange in addition to torsional restraint for 1.6mm thick CFS beam increases the flexural capacity by 14.81% for 10mm lip size and by 13.33% for 15mm lip size. Also, it is found that partial restraint to warping tension in addition to torsional restraint influences the flexural capacity of CFS beam by 25.9% increase for 15mm lip size and by 23.33% for 20mm lip size for the same thickness of 2.0mm.It is observed from the experimental study that partial restraint to warping provided to compression flange influences greatly on the flexural capacity of CFS beams than warping restraint provided to tension flange. Also it is found that flexural capacity of both warping and torsionally restrained CFS beam decreases when lip size increases by 6.3% for 10mm to 15mm, by 2.9% for 15mm to 20mm. Test results are compared with the results obtained from BS 5950, Part 5 in Table IV. The close agreement between the two moments thus verified the accuracy of gravity load readings. The mean value of the ratio of experiment to predicted results (M_{Ltb}/M_b) is 1.03 for torsionally restrained beams, 1.065 for warping and torsionally restrained beams, 1.13 for warping (compression flange only) and torsionally restrained beams and 1.097 for warping (Tension flange only) and torsionally restrained beams.

A. Vertical Deflection Curves

The experimental curves of applied moment versus vertical deflection and lateral deflection at mid span and 1/3rd span of test beams were presented. From these figures, it could be seen that the moment Vs vertical and lateral deflection curves were non-linear. However, there was a linear relationship in moment Vs vertical deflection up to 80% of the ultimate moment. For moment Vs lateral deflections, there was a linear behavior in the beginning stage: The lateral buckling tests of CFS beams by Bogdan et.al (1999) and Cold-Formed RHS beams presented by Zhao et al (1995) had shown similar relationships between the applied moment and deflections. From Fig.10, it can be noticed that the sections with different slenderness have different in-plane and out-of-plane stiffness. It was measured that the maximum in plane deflection was achieved with the beam sections having less slenderness values whereas the maximum out of plane deflection was achieved with the more slender beam sections. This development was realized as the less slender beams can resistant larger moments than the more slender beams before it fails by lateral distorsional buckling (i.e. out of plane buckling). This could be due to certain experimental errors. By comparing the load-deflection behavior of less slender beams with more slender beams, less slender beams clearly demonstrate a peak load and load drop off in their corresponding graphs.

V. Conclusions

The flexural-buckling (Lateral-torsional) tests on CFS lipped channel beams for different boundary conditions were conducted in a purpose-built test rig. The support and loading systems were specially designed to satisfy the idealized boundary conditions required for such flexural buckling tests. The tests included 12 different section geometries, giving a total of 16 flexural buckling tests. The non-linear behavior of CFS lipped channel beams with defined boundary conditions was discussed using moment versus deflection and longitudinal strains for various sections. The influence of warping and torsional restraint on the flexural capacity of the CFS beams was also presented and discussed. The flexural buckling test results were compared with the predictions of member capacities calculated using BS 5950 Part 5 British Code and IS code 801-1975. The test results were in good agreement with the results derived using BS 5950-Part 5.

- Warping and Torsional restraint provided at the supports increases the flexural capacity substantially to a greater extent.
- Warping restraint provided to the compression flange has more influence on the flexural capacity than warping restraint provided to tension flange

It is concluded from the experimental study that lip size of 15mm and 2.0mm thickness will be the optimum size considering flexural-torsional buckling of CFS beams under restrained boundary conditions. Due to warping restraint, CFS beams have more flexural capacity(i.e. 46.67%) than torsionally restrained beams under restrained boundary conditions. All the results would then be used to develop accurate design rules for CFS lipped channel beams under restrained boundary conditions subjected to flexural bending.

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Notations

The following symbols are used in this paper.

A = Cross-sectional area
C_w = Warping constant
E = Young’s modulus of elasticity
E_o = Initial elastic modulus
G = Shear modulus of elasticity
J = Torsion section constant
L = Member Length
M_m = Maximum bending moment
M_E = Elastic lateral Buckling resistance moment
I_1 = Second moment of area about an axis through the web
I_2 = Second moment of area about the neutral axis perpendicular to the web
α_m = Modification factor
β = Ratio of end moments
σ = Proof Stress
σ_p = Proportionality stress
δ = Poisson’s ratio
Υ = $I - \frac{I_1}{I_2}$

Table I. Nominal and Measured Properties

Test Series	**Nominal $\sigma_{0.2}$ (MPa)**	**Measured**			
		$\sigma_{0.2}$(MPa)	**σ_u(MPa)**	**E(MPa)**	**$\varepsilon_{u\,\%}$**
CFS 1.6	400	428	478	2.01×10^5	13.8
CFS 2.0	400	402	492	2.01×10^5	12.9
CFS 2.5	400	431	565	2.01×10^5	14.8
CFS 3.0	400	408	463	2.01×10^5	13.4

Table II. Boundary Conditions at Supports

Sl.No.	**Type**	**Conditions of Restraint at supports**	
		Torsion Restraint *	**Warping Restraint ****
1	Class A	Fully restrained	Warping not restrained in both flange(WF)
2	Class B	Fully restrained	Both flanges fully restrained (WR)
3	Class C	Fully restrained	Compression Flanges Fully Restrained (WR(c))
4	Class D	Fully restrained	Tension Flanges Fully Restrained(WR(T))

* Torsion restraint prevents rotation about the longitudinal axis
** Warping restraint prevents rotation of the Flange in its Plane.

Table III. Specimen Details.

SL. NO	Specimen id	Size(mm)	Thickness	D/t	B/t	d/t	Boundary conditions
1	Aw.N.11	100x50x10	1.6	62.5	31.3	6.3	WFTR
2	Aw.F.11	100x50x10	1.6	62.5	31.3	6.3	WRTR
3	Aw.T.11	100x50x10	1.6	62.5	31.3	6.3	WR©TR
4	Aw.B.11	100x50x10	1.6	62.5	31.3	6.3	WR(T)TR
5	Aw.N.21	100x50x15	1.6	62.5	31.3	9.4	WFTR
6	Aw.F.21	100x50x15	1.6	62.5	31.3	9.4	WRTR
7	Aw.T.21	100x50x15	1.6	62.5	31.3	9.4	WR©TR
8	Aw.B.21	100x50x15	1.6	62.5	31.3	9.4	WR(T)TR
9	Aw.N.22	100x50x15	2.0	50.0	25.0	7.5	WFTR
10	Aw.F.22	100x50x15	2.0	50.0	25.0	7.5	WRTR
11	Aw.T.22	100x50x15	2.0	50.0	25.0	7.5	WR©TR
12	Aw.B.22	100x50x15	2.0	50.0	25.0	7.5	WR(T)TR
13	Aw.N.32	100x50x20	2.0	50.0	25.0	10.0	WFTR
14	Aw.F.32	100x50x20	2.0	50.0	25.0	10.0	WRTR
15	Aw.T.32	100x50x20	2.0	50.0	25.0	10.0	WR©TR
16	Aw.B.32	100x50x20	2.0	50.0	25.0	10.0	WR(T)TR

- WFTR - Warping Free and Torsion Restrained
- WRTR - Torsion Restrained and Warping Restrained Fully
- WR©TR - Torsion Restrained and Warping Restrained at Topside
- WR(T)TR - Torsion Restrained and warping Restrained at Bottom side

Table IV. Comparison of Test results and Code Predictions

Sl. No	**Specimen id**	**Thickness (mm)**	**Exp.values M_{Ltb} (KNm)**	**Buckling moment $M_{b(KNm)}$ (Theoretical as per BS 5950-Part V)**	**Lateral Buckling Moment As per Is code 801-1995 M_{LB} KNm**	**Ratio M_{Ltb}/M_{LB}**	**Lateral Buckling Moment As per from Finite Element Analysis M_{FEA}**	**Ratio M_{Ltb}/M_b**	**Ratio M_{Ltb}/M_{FEA}**
1	Aw.N.11	1.6	2.7	2.36	1.95	1.38	2.623	1.14	2.30
2	Aw.F.11	1.6	3.5	3.22	2.37	1.48	3.549	1.08	3.28
3	Aw.T.11	1.6	3.3	2.76	2.31	1.42	3.316	1.19	2.78
4	Aw.B.11	1.6	3.1	2.55	2.29	1.35	3.086	1.21	2.55
5	Aw.N.21	1.6	3	2.59	2.20	1.36	2.964	1.15	2.57
6	Aw.F.21	1.6	3.7	3.42	2.65	1.68	3.742	1.08	3.46
7	Aw.T.21	1.6	3.6	2.99	2.59	1.39	3.621	1.20	3.01
8	Aw.B.21	1.6	3.4	2.79	2.56	1.32	3.393	1.21	2.80
9	Aw.N.22	2	3	3.24	2.66	1.13	3.111	0.92	3.38
10	Aw.F.22	2	4.4	4.2	3.20	1.38	4.463	1.04	4.29
11	Aw.T.22	2	3.9	3.71	3.12	1.25	4.005	1.05	3.81
12	Aw.B.22	2	3.4	3.47	3.09	1.10	3.421	0.97	3.52
13	Aw.N.32	2	3.2	3.46	2.88	1.07	3.263	0.92	3.54
14	Aw.F.32	2	4.6	4.36	3.42	1.35	4.688	1.06	4.42
15	Aw.T.32	2	4.2	3.91	3.34	1.26	4.290	1.07	4.00
16	Aw.B.32	2	3.7	3.68	3.31	1.12	3.812	1.00	3.81

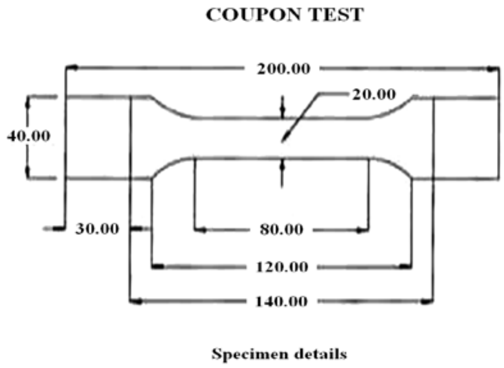


Fig. 1(a). Specimen

Fig.1(b). Failure Pattern

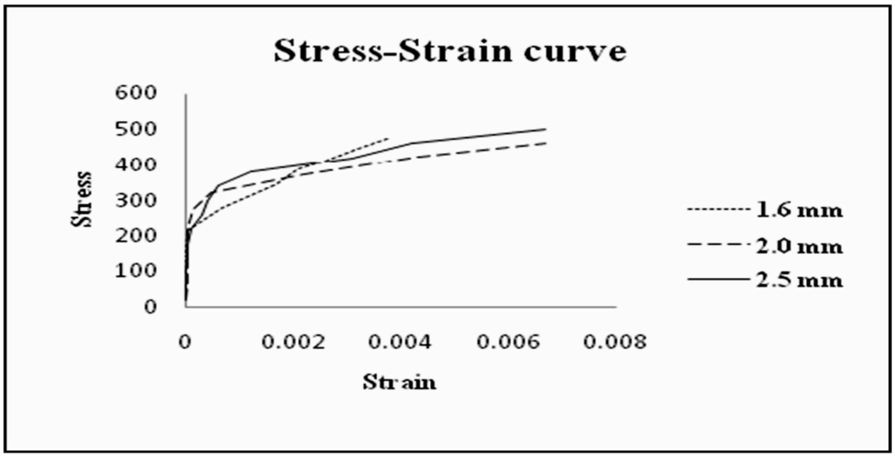
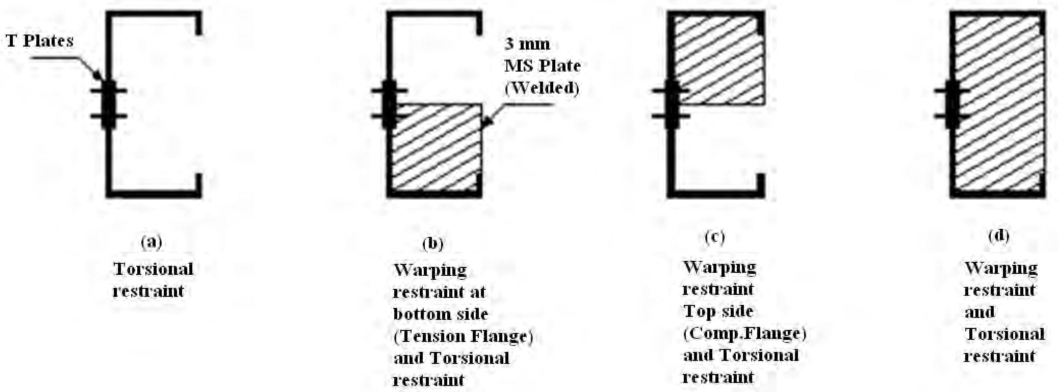


Fig.2. Stress-Strain Curve



(a)
Torsional restraint

(b)
Warping restraint at bottom side (Tension Flange) and Torsional restraint

(c)
Warping restraint Top side (Comp.Flange) and Torsional restraint

(d)
Warping restraint and Torsional restraint

Fig.3. Boundary Conditions

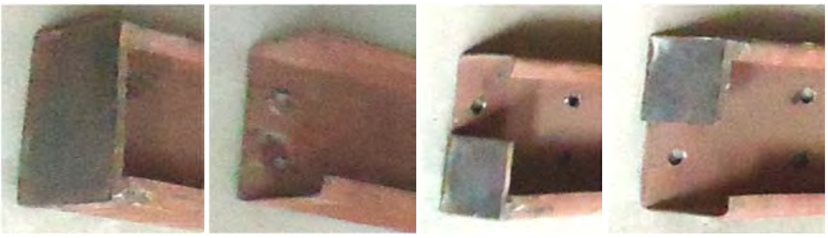


Fig.4. Four Boundary Conditions (Warping)

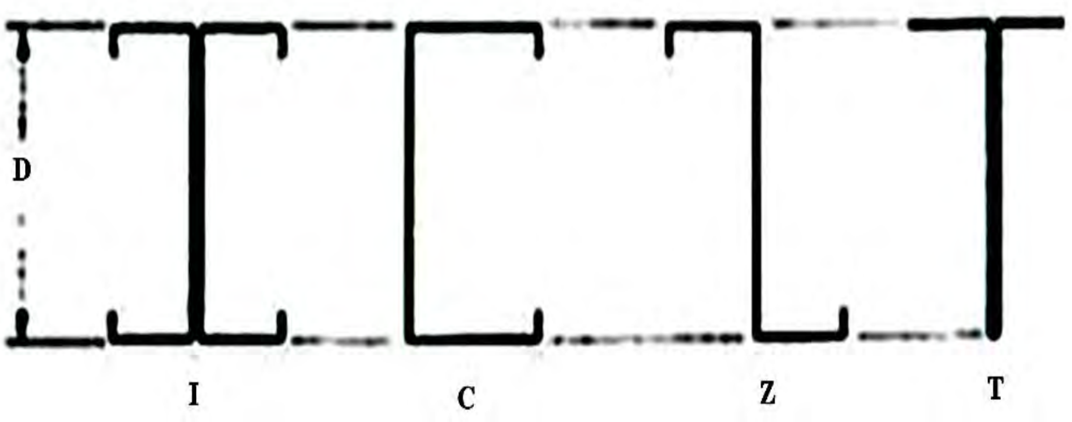


Fig .5. Cross Section covered by the Lateral buckling Clauses of BS 5950 Part 5

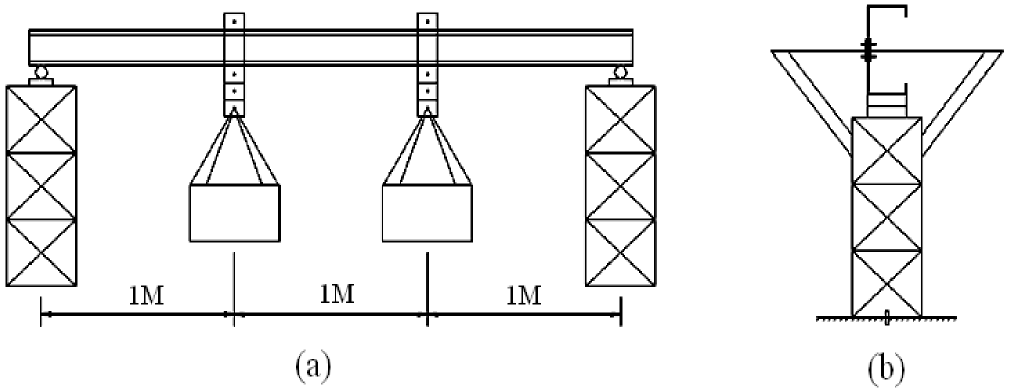


Fig .6 . Longitudinal and Side view of Test setup

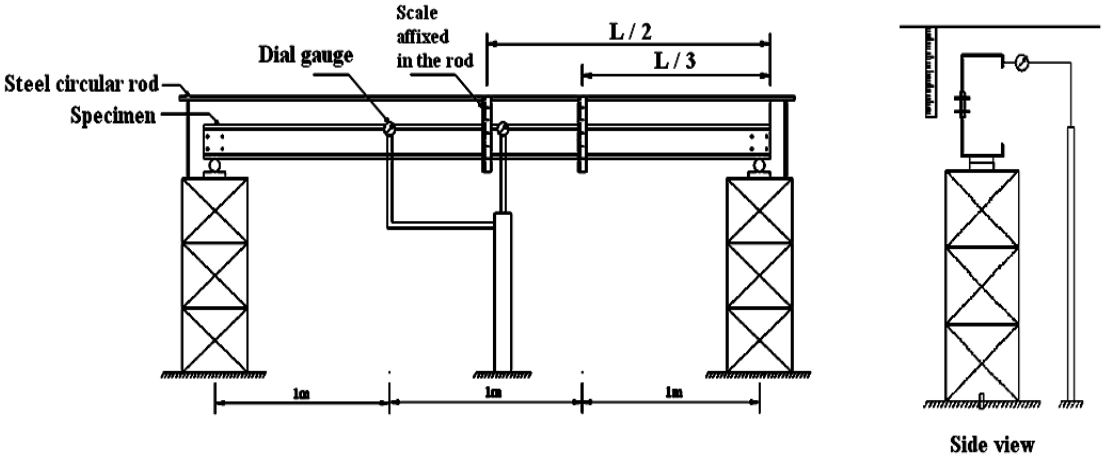


Fig. 7. Schematic view for Measuring System

Fig.8. Test Setup

Fig.9.Failure of a Specimen

Fig.10. Loading pattern and the failure of the beam

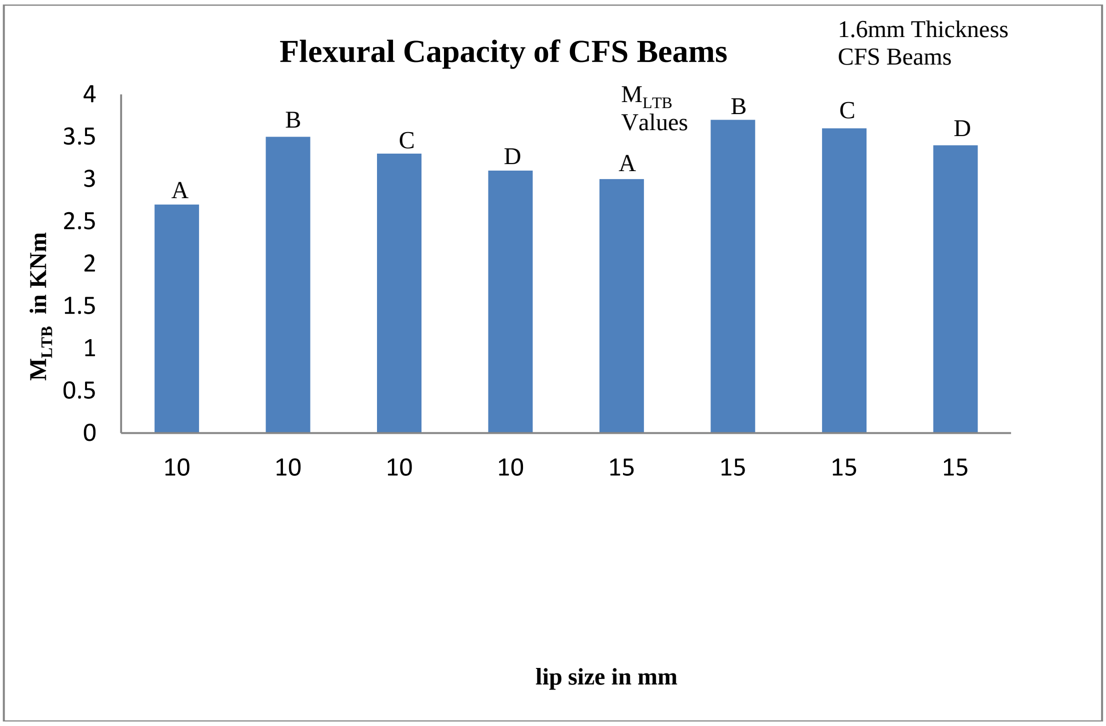


Fig .11. (a)

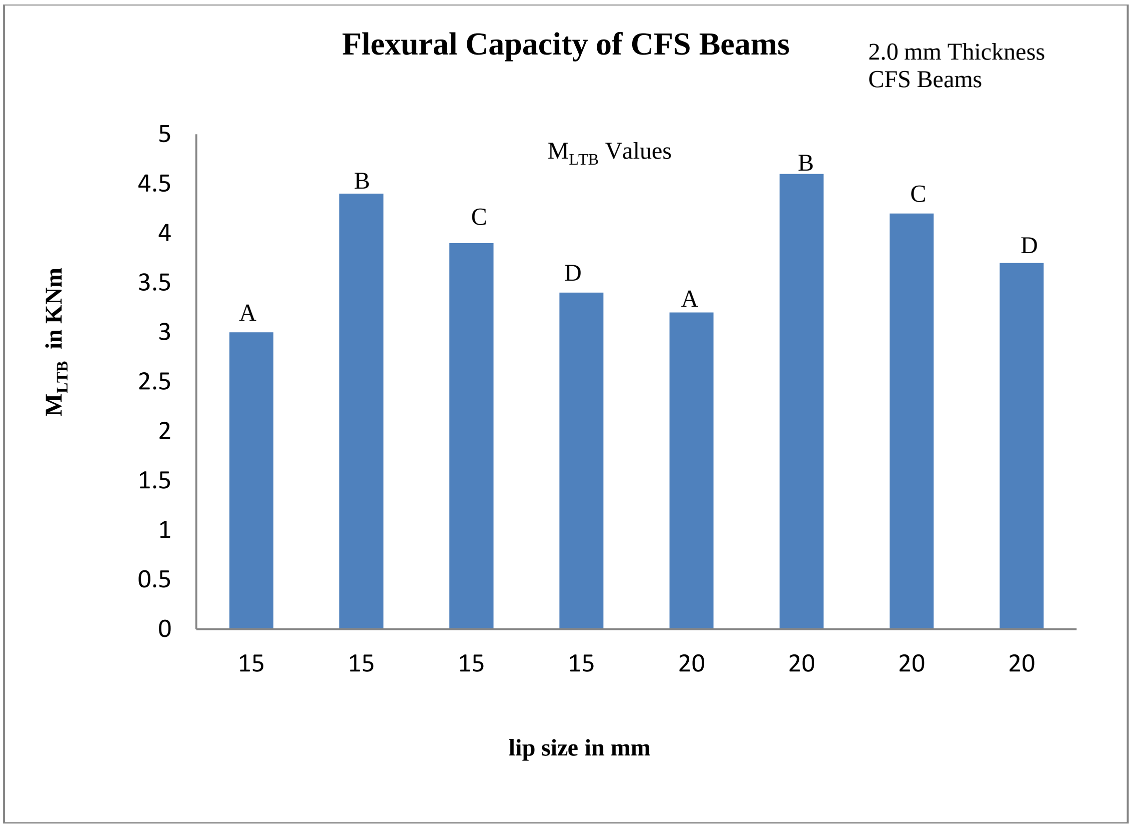


Fig. 11. (b)
Fig.11. Bar Chart showing Flexural Capacity of CFS Beams for 1.6mm and 2.0mm Thickness

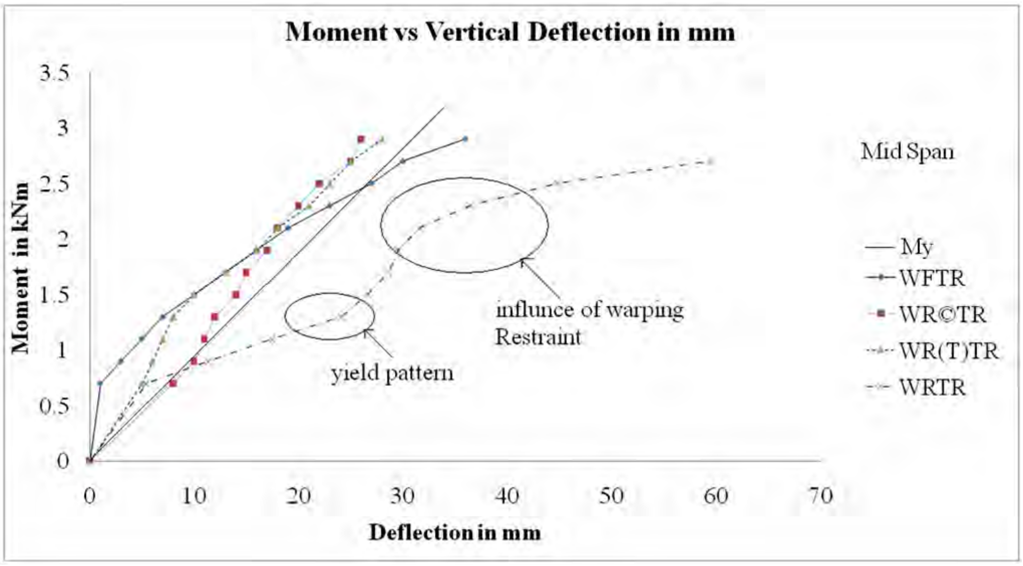


Fig. 12.(a)

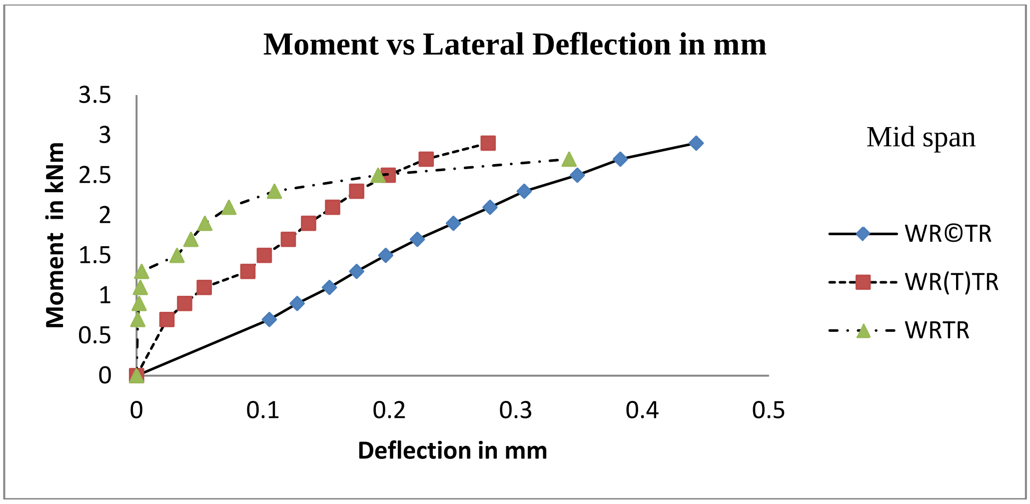


Fig .12. (b)
Fig .12. Moment Deflection Curves

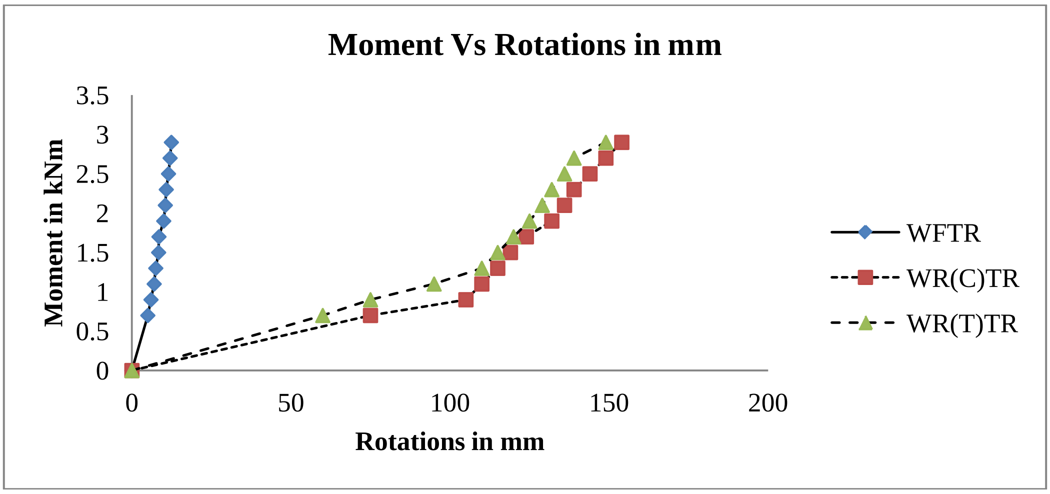


Fig.13. Moment Strain Curves