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SELECTION OF A CURVE FOR HIGH STRENGTH STEEL COLUMNS FROM THE MULTIPLE COLUMN CURVES AND COMPARISON BETWEEN DIFFERENT CODES

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Abstract: *This study describes a test for high strength steel columns fabricated from high strength steel plates. The purpose of the test is to select a curve for high strength steel columns from the multiple column curves used in the IS 800:2007. It is shown that* $"\alpha"=.49$ *curve is the appropriate curve for I-section column fabricated from flame cut high strength steel plates. This curve is higher than the curve for I-section columns fabricated from ordinary steel because the effect of residual stress is less detrimental to the high strength steel columns than to the strength of ordinary steel columns. The study also shows a comparison of test strength with column design strengths of the Indian Standard 800:2007, the Australian steel structures standard AS4100, the load and resistance factor design specification of the American Institute of Steel Construction, the British Standard BS5950: part 1 and the draft European committee for standardization Eurocode 3.*

Keywords: *Yield stress, partial safty factor, ultimate load, design compressive strength, effective column length, imperfection factor.*

I. INTRODUCTION

The scope of current Indian standard for steel structure is limited to ordinary steel with yield stress less than 450 MPa. Consequently in India, structural members fabricated from high strength steel (defined in this paper as steel with a yield stress in excess of 450 MPa) are usually designed according to overseas specifications which allow the use of high strength steel, notably the American Institute of Steel Construction (AISC) Load and Resistance Factor Design (LRFD) specification.

This study describes the strength of members fabricated from high strength steel. The aim of the study is to investigate whether high strength steel members with yield stress in range from 450MPa to 700MPa can be designed according to the existing rules of the Indian standard (IS800: 2007) whether these rules need to be modified to include high strength steel.

II. METHODOLOGY

2.1 Design strength of compression member

The term compression member is generally used to describe structural components subjected to axial compression loads. Column, top chords of trusses, diagonals and bracing members are all exemplas of compression member columns are usually thought of as straight compression members whose lights are considerably greater than their cross- sectional dimensions.

2.1.1 Cross section of compression members

For optimum performance compression members need to have a high radius of gyration in the direction where buckling can occur, circular hollow sections should therefore be most suitable in this respect as they maximize this parameter in all directions. The connections to these sections are, however, expansive and difficult to design.

It is also possible to use square or rectangular hollow sections whose geometrical properties are good (square hollow sections being the better); the connections are easier to design than those of the previous shape, but again rather expansive.

Hot-rolled sections are, in fact the most common cross-sections used for compression members. Most of them have large flanges designed to be suitable for compression loads. Their general square shape gives a relatively high transverse radius of gyration and the thickness of their flanges avoids the effect of local buckling.

Welded box or welded I-sections are suitable if care is taken to avoid local flange buckling. They can be designed for the required load and are easy to connect to reinforce these shapes with welded caver plates.

Built-up columns are fabricated from various different elements; they consist of two or more main compounds, connected together at intervals to form a single compound member. Channel sections and angles are often used as the main components but it is also possible to use I-section; they are laced or battened together with simple elements (bars or angles or smaller channel section).

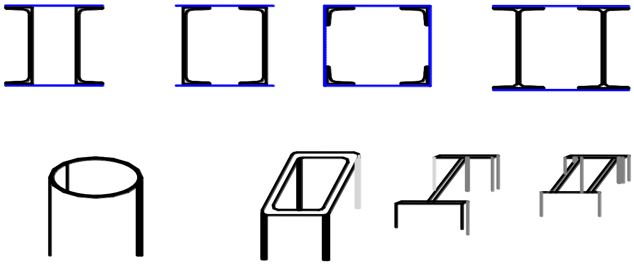

Fig. 1: Cross sections of compression members

2.1.2 Behaviour of Compression member

Compression members are sometimes classified as being long, short and intermediate. Brief discussions about this classification along with the behavior are as follow:

2.1.2.1 Short compression member (Stub or stocky columns)

Short compression member (Stub or stocky columns) are characterised by very low slenderness, are not effected by buckling and can be designed to the yield stress f_y.

If local buckling does not affect the compression resistance (as can be assumed for Plastic (Class 1), Compact (Class 2), and Semi-compact (Class 3) cross sections), the mode of failure of such members corresponds to perfect plastic behaviour of the whole cross-section, which theoretically occurs when each fiber of the cross-section reaches f_y. It is to be noted that residual stresses and geometric imperfections are practically without influence on the ultimate strength of this kind of column and that most experimental stub columns fail above the yield stress because of strain-hardening. The maximum compression resistance P_{max} (N_{max}) is, therefore, equal to the plastic resistance of the cross-section:

$$P_{\max}(N_{\max}) = A_{eff}\, f_y$$

Where, A_{eff} = the effective area of the cross-section

f_y = Yield stress

IS 800: 2007 had adopted same multiple column curves (modified ECCS curves developed by European countries). The ECCS curve considers that columns are stocky when their effective slenderness ratio λ is such that $\lambda \le 0.2$.

2.1.2.2 Long compression member (High slenderness)

For these compression member the Euler formula, predicts the strength of long compression member very well, where the axial buckling stress remain below the proportional limit. Such compression member buckles elastically.

2.1.2.3 Intermediate length compression member (Medium slenderness)

For intermediate length compression member, some fibers would have yielded and some fiber will still be elastic. These compression members will fail both by yielding and buckling and their behaviour is said to be inelastic.

The detailed behaviour of long and medium length compression member is discussed in next article "Stability of slender steel column".

2.1.3 Stability of slender steel columns

Depending on their slenderness, columns exhibit two different types of behaviour: those with high slenderness present a quasi elastic buckling behaviour whereas those of medium slenderness are very sensitive to the effects of imperfections.

Euler Critical Stress: If λ_{eff} is the effective length (critical length), the Euler critical load $P_{cr}(N_{cr})$ is equal to:

$$P_{cr}(N_{cr}) = \frac{\pi^2 EI}{\lambda_{eff}^2} \qquad \ldots(1)$$

and it is possible to define the Euler critical stress σ_{cr} as:

$$\sigma_{cr} = \frac{P_{cr}(N_{cr})}{A} = \frac{\pi^2 EI}{\lambda_{eff}^2 A} \qquad \ldots(2)$$

By introducing the radius of gyration $r(i) = \sqrt{\frac{I}{A}}$, and the slenderness $\left(\frac{KL}{r} \text{ or } \lambda\right) = \frac{\lambda_{eff}}{\gamma}$, for the relevant buckling mode, Equation (2) becomes

$$\sigma_{cr} = \frac{\pi^2 EI}{\lambda_{eff}^2 \left(\frac{KL}{r}\right)^2} = \frac{\pi^2 EI}{\lambda_{eff}^2 \lambda^2}$$

Plotting the curve of Euler critical stress σ_{cr} as a function of slenderness $\left(\frac{KL}{r} \text{ or } \lambda\right)$ on a graph , with the line representing perfect plasticity, $s = f_y$, shown, it is interesting to note the idealised zones representing failure by buckling, failure by yielding and safety.

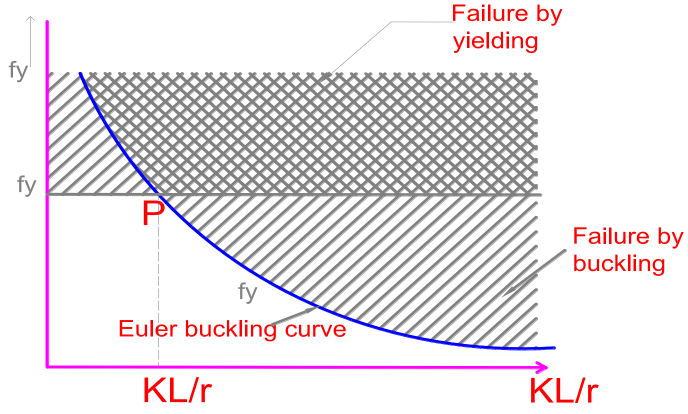

Fig..2: Local buckling curve and modes of failure

The intersection point P, of the two curves represents the maximum theoretical value of slenderness of a column compressed to the yield strength. This maximum slenderness (sometimes called Euler slenderness), called λ_1 in Eurocode 3, is equal to:

$$\lambda_1 = \pi \left[\frac{E}{f_y}\right]^{1/2} = 93.9\varepsilon$$

Where $\varepsilon =$ Yield stress ratio $= \sqrt{\left(\frac{235}{f_y}\right)}$

A non-dimensional representation of this diagram is obtained by plotting $\frac{\sigma}{f_y}$ as a function of $\frac{\lambda}{\lambda_1}$; this is the form used for the ECCS curves . The coordinates of the point P are, therefore, (1.1).

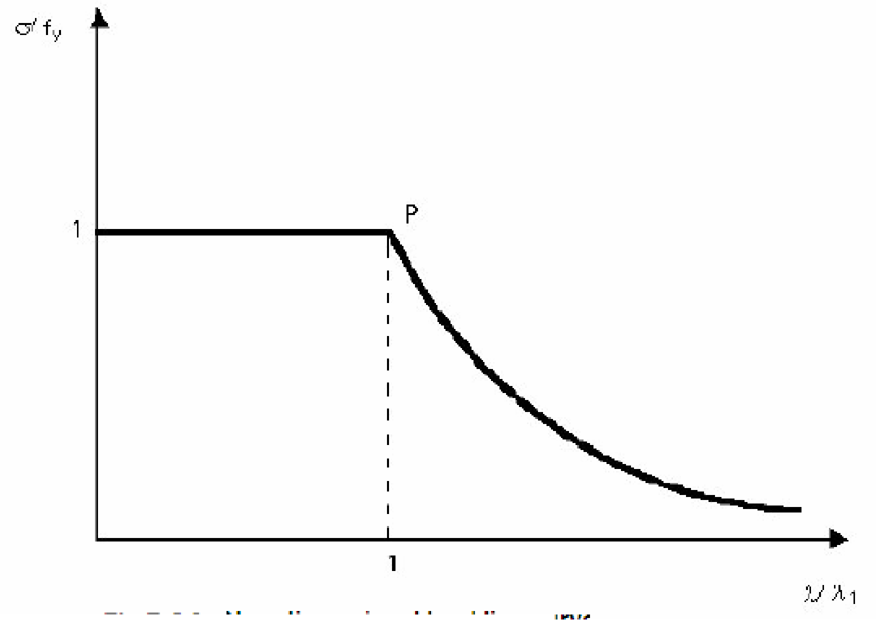

Fig.3: Non-dimensional buckling curve

Buckling of Real Columns

The real behaviour of steel columns is rather different from that described in the previous section and columns generally fail by inelastic buckling before reaching the Euler buckling load. The difference in real and theoretical behaviour is due to various imperfections in the "real" element: initial out-of-straightness, residual stresses, eccentricity of axial applied loads and strain-hardening. The imperfections all affect buckling and will; therefore, all influence the ultimate strength of the column. Experimental studies of real columns give results as shown in Figure 4.

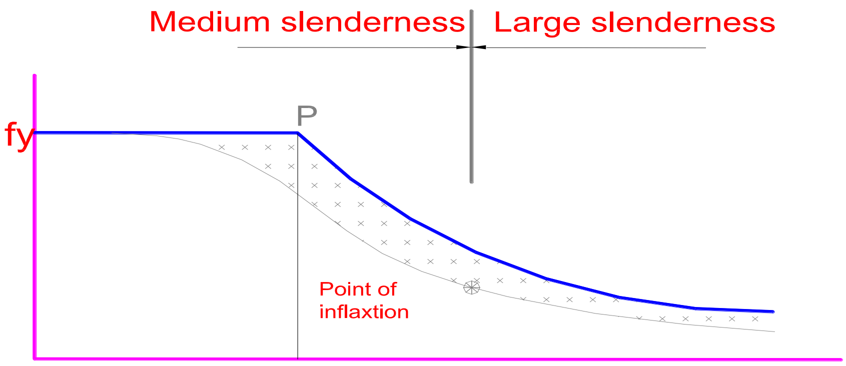

Fig.4: Real column test result and buckling curves

Here following observations are made from figure:

- Compared to the theoretical curves; the real behaviour shows greater differences in the range of medium slenderness than in the range of large slenderness.
- In the zone of the medium values of λ (representing most practical columns), the effect of structural imperfections is significant and must be carefully considered. The greatest reduction in the theoretical value is in the region of Euler slenderness λ_1.
- The lower bound curve is obtained from a statistical analysis and represents the safe limit for loading.

2.2 Test specimen data and fabrication procedure

The test specimen were fabricated by manual gas metal arc welding from nominal 8mm plates of high strength steel. The 8 mm plates were flame cut into strips. The strips were tack welded into section before final welding. A preheat of 50 degree C was used for the 8mm plates. A single run of weld was laid along each fillet so that four runs were laid for each section type. To reduce weld shrinkage deformations, the welds were laid alternatively at four fillets, rather than continuously along each fillet, and were staggered weld length was 400-600mm.

The nominal and measured cross section dimensions of each column shown for I-sections in tables 1 and 2.

2.3 Column test

2.3.1 Geometric imperfections

Overall geometric imperfections are here defined as the deviation of the column axis at mid length from a straight line connecting the ends and denoted by v_0 for I-sections only minor axis imperfections were measured. During measurement the ends were simply supported and the specimen allowed sagging between between the supports. Readings were taken using optical level at the ends and at the centre, allowing the deviation of the column axis at mid length from a straight line connecting to the ends to be calculated. This procedure is repeated after rotating the column by 180 degree about its longitudinal axis, and the two readings were averaged to eliminate gravity effect.

The tables 1 and 2 shows the sectional properties, cross sectional area (A), minor axis second moment of area (I), and radius of gyration (r) of I-section column. The measured specimen length (L) is also shown in tables 1 and 2. The pin ended lengths were obtained as the sum of specimen length and the total length (450 mm) of end bearings.

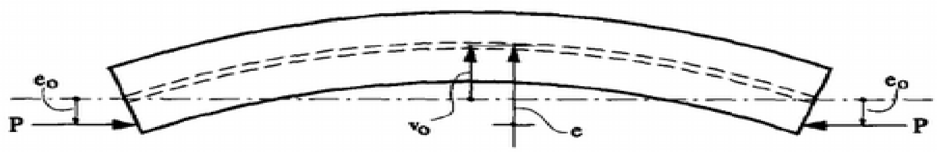

Fig. 5: Loading eccentricity and geometric imperfection

2.3.2 Loading eccentricity

The eccentricity (e_0) of the applied loads at the supports was calculated for each long column during initial loading by measuring the deflection and longitudinal strains at mid length. The eccentricity (e_0) and the total deviation $(e = v_0 + e_0)$ of the centroid at mid length divided by pin ended length (L_t) are shown in table 3.1 and 3.2. The deviation was measured from a straight line connecting the points of application of the forces at the ends.

In the tests of long columns, the specimen was positioned in the rig such that $\frac{e}{L_t} \times 10^3$ was approximately zero and unity for the concentrically and eccentrically loaded columns respectively. The measured values of $\frac{e}{L_t} \times 10^3$ differ slightly from these nominal values, reflecting the difficulty of positioning the specimen accurately in the rig.

2.3.3 Test procedure

The long columns were tested between pinned end bearings in a horizontal servo-controlled Dartec test rig. The instrumentation of the pin ended columns consisted of a load cell measuring the axial force, transducer measuring axial compression, deflections in principal directions at mid length, and the end rotation, as well as strain gauges measuring longitudinal strain at mid length. After exceeding the proportionality stress of the material, readings were taken approximately 1 Min after applying an increment of shortening to allow the stress relaxation associated with the mobilization and locking of dislocations between metal crystals to take place.

Table 1: Non Dimensional Test Strengths of I-Section Columns

Specimen	v_0 (mm)	e_0 (mm)	$\frac{e}{L_t} \times 10^3$	$\frac{P_u}{(A.\sigma y_t)}$
I1000C	0.0	0.7	0.70	0.952
I1000E	0.1	1.2	1.30	0.991
I1650C	0.3	0.1	0.25	0.800
I1650E	0.5	0.5	0.61	0.762
I2950E	0.6	1.4	0.68	0.337
ISC	–	–	–	1.077

Table 2: Measured Dimensions and Ultimate Loads of I-Section Test Specimens

Specimen	B_f	b_f	t_f	b_w	t_w	L	A	I	R	P_u
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
Nominal section	140	66	8	140	8	–	3430	3.66×10^6	32.7	–
11000C	141.5	66.9	7.70	140.0	7.70	550	3329	3.64×10^6	33.1	2092
11000E	141.1	66.7	7.67	141.8	7.71	550	3350	3.60×10^6	32.8	2192
11650C	141.5	66.9	7.70	141.5	7.66	1199	3315	3.64×10^6	33.1	1751
11650E	141.5	66.9	7.71	143.0	7.75	1199	3346	3.65×10^6	33.0	1682
12950E	140.3	66.3	7.75	142.0	7.74	2500	3351	3.57×10^6	32.6	745
ISC	140.0	66.1	7.73	142.0	7.73	400	3334	3.54×10^6	32.6	2369

III. DESIGN AND ANALYSIS

3.1 Column design as per rules of IS 800: 2007

The design compressive strength P_d, of a member is given by:

$$P < P_d$$

Where, $P_d = A_{e.} f_{cd}$

Where $A_{e.}$ = effective sectional area

f_{cd} = design compressive stress

The design compressive stress f_{cd}, of axially loaded compression members shall be calculated using the following equation:

$$f_{cd} = \frac{\dfrac{f_y}{\gamma_{mo}}}{\phi + \left[\phi^2 - \lambda^2\right]^{0.5}}$$

Where, $\phi = 0.5(1+\alpha \quad (\lambda - 0.2) + \lambda^2)$

λ = non-dimensional effective slenderness ratio

$$\lambda = \sqrt{\frac{f_y}{f_{cc}}}$$

f_{cc} = Euler buckling stress

$$f_{cc} = \frac{\pi^2 E}{\left(\dfrac{KL}{r_z}\right)^2}$$

Where, $\dfrac{KL}{r}$ = effective slenderness ratio or ratio of effective length, KL to appropriate radius of gyration,

α = imperfection factor

χ = stress reduction factor for different buckling class, slenderness ratio and yield stress

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \lambda^2}}$$

for different buckling class, slenderness ratio and yield stress

γ_{mo} = partial safety factor for material strength.

$\gamma_{mo} = 1.1$

Table 3: Imperfection Factor "α"

Buckling class	a	b	c	D
α	0.21	0.34	0.49	0.76

Table 4: Test Strengths of I-Section Columns

Specimen	Test strength (kN)
I1000C	2091.677
I1000E	2191.101
I1650C	1750.320
I1650E	1682.770
I2950E	745.329

Table 5: Ultimate load of compression members using IS 800:2007

specimen	Ultimate load Pu (KN)			
	Curve a	Curve b	Curve c	Curve d
I1000C	2153.197	2120.240	2089.480	2034.551
I1000E	2160.147	2133.615	2102.661	2042.964
I1650C	1907.848	1780.950	1660.616	1485.584
I1650E	1927.898	1793.188	1671.728	1495.059
I2950E	968.707	882.452	807.255	703.307

3.2 column curve selection

As the strength of column is affected by residual stresses and eccentricities of load, IS 800: 2007 define buckling classes a, b, c and d depending upon imperfection factor.

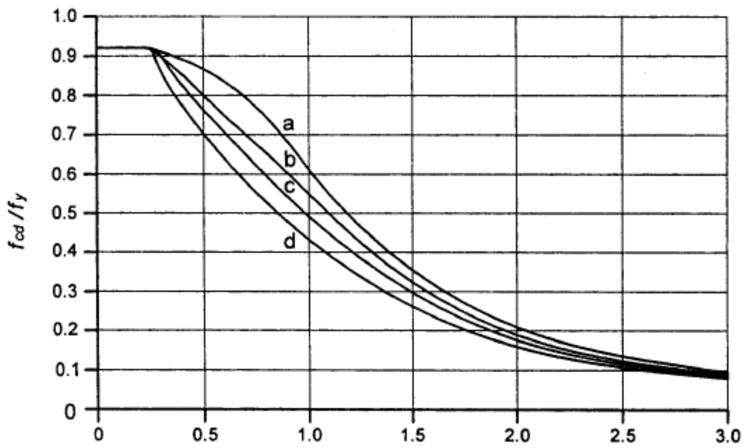

Fig. 6: Column buckling curve

On the basis of comparison between test strength, design strength and ultimate load of different I-section high strength steel columns, it has been recommended that the $\alpha_b = 0.49$ curve to be used in the Indian standard for welded I-sections columns (minor axis buckling) fabricated from flame-cut high strength steel plate (t < 40 mm) .

3.3 Comparison of test strengths with the Indian, Australian, American, British and European Specifications for steel structures

The test results of the I-section columns are compared in the fig 4.2 with design strengths obtained using the Australian, American, British and European specifications for steel structures. The comparison is based on nominal cross section, and nominal yield stress.

The Eurocode3 design curves shown in fig 7 are based on section 5.5.1 of the specification. (Annex D of Eurocode3 allows a higher design curve to be used for

I-sections of nominal 420 and 460 MPa yield stress than the sections of ordinary European steel, having nominal yield stress of 225, 275 and 355 MPa. However this annex applies specifically to hot rolled sections.)

For each specification, the component plates of the cross sections were sufficient stocky that the section capacity was equal to the squash load. However in using British standard, the design strength was reduced by 20 MPa in accordance with section 4.7.5 of that standard because the columns were fabricated by welding.

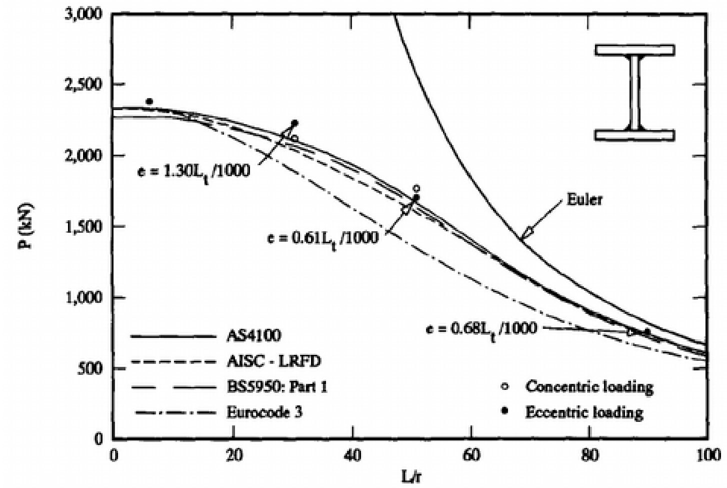

Fig. 7: Comparison of design strengths and test strengths for I section columns using nominal values

ECCS Buckling Curves

From 1960 onwards, an international experimental programme was carried out by the ECCS to study the behavior of standard columns. More than 1000 buckling tests, on various types of members (I, H, T, U, circular and square hollow sections), with different values of slenderness (between 55 and 160) were studied. A probabilistic approach, using the experimental strength, associated with a theoretical analysis, showed that it was possible to draw some curves describing column strength as a function of the reference slenderness. The imperfections which have been taken into account are: a half sine-wave geometric imperfection of magnitude equal to 1/1000 of the length of the column; and the effect of residual stresses relative to each kind of cross¬section. The European buckling curves (a, b, c or d) are shown in Figure 7. These give the value for the reduction factor χ of the resistance of the column as a function of the reference slenderness for different kinds of cross¬sections (referred to different values of the imperfection factor α).

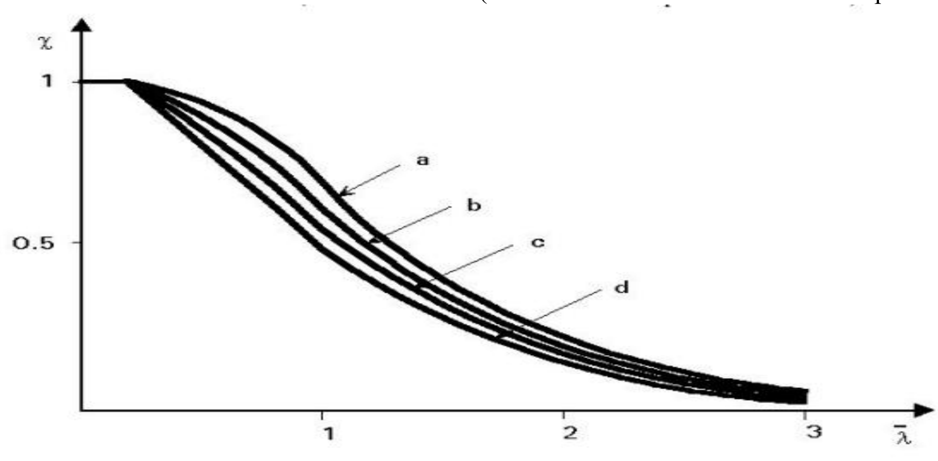

Fig. 8: European buckling curve

In the following comparison, the Eurocode 3 adoption of the Rondal Maquoi approximation to multiple ECCS, “a”, “b”, and “c” column curves is used as reference. Consequently, using a notation consistent with that of section 3.1, the ECCS, “a”, “b”, and “c” curves are approximated closely by slenderness reduction factor,

$$\alpha_c = \frac{1}{\phi + \sqrt{\phi^2 - \overline{\lambda}^2}} \leq 1 \quad \text{...(1)}$$

Where,

$$\phi = \frac{1}{2}\left[(1+\eta) + \overline{\lambda}^2\right] \quad \text{...(2)}$$

$$\overline{\lambda} = \sqrt{\frac{f_y}{f_E}} \quad \text{...(3)}$$

$$f_E = \frac{\pi^2 E}{\left(\frac{Le}{r}\right)^2} \quad \text{...(4)}$$

$$\eta = \alpha\left(\overline{\lambda} - 0.2\right) \quad \text{...(5)}$$

$\alpha = 0.21$ "a" curve ...(6)
0.34 "b" curve
0.49 "c" curve
0.76 "d"curve

It follows from these equations that for a given value of α, the slenderness reduction factor is uniquely defined by the slenderness $\overline{\lambda}$.

The curves of the Indian, Australian, American, British and European specifications are obtained on the following basis.

- In using the Indian standard, the $\alpha = 0.49$ curve is the close fit to the "c" curve of the ECCS Recommendations.
- In using the Australian standard, the $\alpha_b = -0.5$ curve is a close fit to the "a" curve of the ECCS Recommendations.

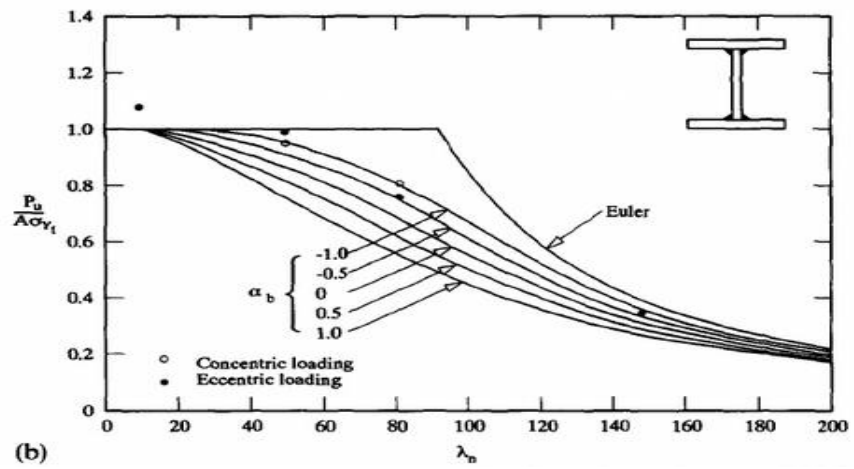

Fig. 9: Column curves of AS4100 for I section columns

- The American specification has not adopted the multiple column curve concept, but uses a single curve which is fit to the SSRC 2P curve. The SSRC 2P curve is based on a mean overall geometric imperfection of $\frac{1}{1470}$ of the length. And lies between "a" and "b" curve of the ECCS recommendations at intermediate and long column lengths but below the curve "b" at short lengths.
- The column curves of British standard are defined by equations (1) to (6), except that the imperfection parameter is given by

$$\eta = 0.001a\sqrt{\frac{\pi^2 E}{f_y}}\left(\overline{\lambda} - 0.2\right) \quad \text{...(7)}$$

Rather than by equation (5). The constant a takes the values 2.0, 3.5 and 5.5 for the British "a", "b" and "c" curves respectively. Consequently, in using the British standard, the slenderness reduction factor is a function of yield stress. The curve to be used for I-section (minor axis bending) columns fabricated from flame-cut plates $(t \leq 40 \text{ mm})$ is the "b" curve. For mild steel $(f_y = 235MPa)$ is the curve concide with ECCS "b" curve.

But for high strength steel the imperfection parameter becomes,

$$\eta = 0.190(\bar{\lambda} - 0.2)$$

and so for this value of yield stress the British "b" curve is nearly the same as ECCS "a" curve almost slightly higher.

- The Eurocode3 column curves are defined by equations (1) to (6). The curve specified for welded I-section column bent about their minor axis, the specified column curve is the "c" curve. This curve is similar as the curve specified in IS800:2007 and lower than those specified in AS4100 and BS5950, partly because I-section fabricated from flame cut plates may be designed using a higher column curve than sections fabricated from as-rolled plates according to AS4100 and BS5950, whereas no such distinction is made in Eurocode3.

IV. RESULT AND DISCUSSION

1. From the analysis and design work the design strength of high strength steel columns fabricated from flame-cut high strength steel plates (t < 40 mm) were obtained and compared with the test strength. On the basis of comparison between test strength and design strength of different I-section high strength steel columns, it has been recommended that the $\alpha = 0.49$ curve (IS800:2007 "c" curve and ECCS "c" curve) to be used in the Indian standard 800: 2007 for welded I-sections columns (minor axis buckling) fabricated from high strength steel plates (t < 40 mm).
2. For the Australian standard, the $\alpha_b = -0.5$ curve is a close fit to the "a" curve of ECCS Recommendations and it is recommended to be used in the Australian standard for welded I-sections columns.
3. The American specification has not adopted the multiple column curve concept, but uses a single curve which is fit to the SSRC 2P curve. The SSRC 2P curve is based on a mean overall geometric imperfection of $\frac{1}{1470}$ of the length. And lies between "a" and "b" curve of the ECCS recommendations at intermediate and long column lengths but below the curve "b" at short lengths.
4. In using the British standard, the slenderness reduction factor is a function of yield stress. The curve to be used for I-section (minor axis bending) columns fabricated from flame-cut plates $(t \leq 40 \text{ mm})$ is the "b" curve. For mild steel $(f_y = 235MPa)$ is the curve concide with ECCS "b" curve, but for high strength steel the imperfection parameter becomes,

   $$\eta = 0.190(\bar{\lambda} - 0.2)$$

   and so for this value of yield stress the British "b" curve is nearly the same as ECCS "a" curve almost slightly higher.
5. For Eurocode3 the curve recommended for welded I-section columns bent about their minor axis, is the "c" curve. This curve is similar as the curve recommended for IS 800: 2007.

V. SUMMARY AND CONCLUSION

The state-of-the-art design finds its way into practice through specifications and stipulations of relevant codes. In India, several development works has taken place for improving the material properties of steel, yet the design is uneconomical at times due to non-availability of efficient sections. From the result of this project work we can conclude that high strength steel columns fabricated from flame-cut high strength steel plates (t < 40 mm) can be designed by selecting curve "c" with imperfection factor $\alpha = 0.49$ of column buckling curve used in IS 800: 2007.

The column curves of the Australian, American and British specifications to be used in the comparison with test strengths all fit closely to the ECCS "a" curve. However the column curves specified in Eurocode3 and in Indian standard are "c" curve for welded I-sections bent about their minor axis.

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