

# Design Aids of Flexural Members and Beam-Columns Based on Limit State Method

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**ABSTRACT:** The latest version of the Code of Practice for general construction in steel, IS 800-2007 is based on Limit State Method of design. The design concept is totally changed in comparison to earlier code IS-800-1984 which is based on elastic method. The design based on limit state method involves many equations and parameters. Therefore the design of steel structural members and connections involves tedious equations. In the present work, the detailed study has been carried out on the design of flexure members and beam-columns for channel section and effort is made to prepare design aids in the form of graphs, which is very useful to the practicing Structural Engineers. The use of charts for the design of flexure members and beam-columns will save the steel designer's time considerably.

**KEYWORDS:** IS:800-2007, Factored load.

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## 1. Introduction

The structural/civil Designer has to ensure that the structures and facilities he designs are (i) fit for their purpose (ii) safe and (iii) economical and durable. Thus safety is one of the paramount responsibilities of the designer. However, it is difficult to assess at the design stage how safe a proposed design will actually be – consistent with economy. There is, in fact, a great deal of uncertainty about the many factors, which influence both safety and economy. Firstly, there is a natural variability in the material strengths and secondly it is impossible to predict the loading, which a structure (e.g. a building) may be subjected to on a future occasion. Thus uncertainties affecting the safety of a structure are due to

- Uncertainty about loading
- Uncertainty about material strength and
- Uncertainty about structural dimensions and behaviour.

These uncertainties together make it impossible for a designer to guarantee that a structure will be absolutely safe.

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All that the designer could ensure is that the risk of failure is extremely small, despite the uncertainties. Earlier for designing steel structures working stress method is used (IS: 800-1984). Now designing done using limit state method (IS: 800-2007).

Design is basically a trial and error process, initially a section is assumed and it is checked, for its capacity to withstand the applied load. In case of design of steel structural elements according to IS: 800-2007, no ready to-use design tools are available to aid the initial selection.

## 2. OVERVIEW OF DESIGN EQUATIONS AS PER IS: 800-2007

### 2.1 Effective Span of Beams

The effective span of a beam shall be taken as the distance between the centre of the supports, except where the point of application of the reaction is taken as eccentric at the support, when it shall be permissible to take the effective span as the length between the assumed lines of the reactions.

### 2.2 Design bending strength of laterally Supported Beams

The design bending strength of beams, adequately supported against buckling (laterally supported beams) is governed by yielding stress.

The factored design moment,  $M$  at any section, in a beam due to external actions shall satisfy

$$M \leq M_d$$

Where  $M_d$  = design bending strength of the section

Based on Shear force  $V$  values the design bending strength  $M_d$  of a beam may be computed as follows (refer IS 800:2007 clause 8.2.1):

**2.2.1 When shear force  $V < 0.6 V_d$  (refer IS 800:2007 clause 8.2.1.2) where  $V_d$  is design shear strength of the cross-section.**

$$M_d = (\beta_b Z_p f_y) / \gamma_{m0} \leq 1.2 Z_e f_y / \gamma_{m0} \text{ for simply supported beam} \quad (1)$$

$$\leq 1.2 Z_e f_y / \gamma_{m0} \text{ for cantilever supported beams}$$

**2.2.2 When shear force  $V > 0.6 V_d$  (refer IS 800:2007 clause 8.2.1.3)**

The design bending strength  $M_d$  shall be

$$M_d = M_{dv} \quad (2)$$

$M_{dv}$  = design bending strength under high shear (as per clause 9.2.2)

$$= M_d - \beta (M_d - M_{rd}) = 1.2 Z_e f_y / \gamma_{m0} \text{ for Plastic or Compact section} \quad (3)$$

**2.3 Design Bending strength of Laterally Unsupported Beams**

If the laterally unrestrained length of the compression flange of the beam is relatively long then a phenomenon known as lateral buckling or lateral torsional buckling of the beam may take place and the beam would fail well before it can attain its full moment capacity. Resistance to lateral torsional buckling need not be checked separately in the following cases:

- a) bending is about minor axis of the section
- b) section is hollow (rectangular/tubular) or solid bars
- c) in case of major axis bending,  $\lambda_{LT} = \chi_{LT} f_y / \gamma_{m0} < 0.4$

The design bending strength of laterally unsupported beams as governed by lateral torsional buckling is given by (refer IS800:2007 clause 8.2.2):

$$M_d = \beta_b Z_p f_{bd} \quad (4)$$

$$f_{bd} = \chi_{LT} f_y / \gamma_{m0} \quad (5)$$

(refer IS 800:2007, table 13a and 13b, page nos. 55 and 56)

**2.4 Strength of Beam-Columns**

The behaviour of beam-columns is fairly complex, particularly at the ultimate stage and hence exact evaluation of the strength would require fairly complex analysis. However, for design purposes, simplified equations are available, using which it is possible to obtain the strength of members, conservatively.

**2.5 Design of Beam-Columns Subjected to Compression and Bending**

**Local capacity check** The following simplified interaction equation is specified in the code for the beam-column subjected to combined axial force and bending moment (clause 9.3.1.1 for plastic, compact and semi-compact section)

$$(N/N_d) + (M_y/M_{dy}) + (M_z/M_{dz}) \leq 1.0 \quad (6)$$

where  $M_{dy}$  and  $M_{dz}$  are the design reduced flexural strength under combined axial force and the respective uniaxial moment acting alone,  $M_y$  and  $M_z$  are the factored applied moments along minor and major axis of the cross section, respectively,  $N_d$  is the design strength in compression obtained from Section 6 of the code, and  $N$  is the factored applied axial compressive force.

**Overall buckling check** The code stipulates that the member should be checked for lateral-torsional buckling under reduced effective moment  $M_{eff}$  due to tension and bending. The reduced effective moment is given by the code as clause 9.3.2.1.

$$M_{eff} = [M - TZ_{ec} / A] \leq M_d \quad (7)$$

where  $M$  and  $T$  are the factored applied moment and tension, respectively,  $A$  is the area of cross section,  $Z_{ec}$  is the elastic section modulus of the section with respect to extreme compression fibre,  $\psi = 0.8$ , if  $T$  and  $M$  vary independently and 1.0 otherwise, and  $M_d$  is the bending strength due to lateral-torsional buckling.

**2.6 Slenderness Ratio**

$$\lambda = KL/r \quad (8)$$

IS: 800-2007 specifies limiting (maximum) slenderness ratio for Flexural members  $\lambda > 300$  not permitted and for Beam-Column  $\lambda > 250$  not permitted.

**3. Design charts for Flexural Members**

The Charts have been prepared based on IS: 800-2007 for laterally supported and laterally unsupported beams. The procedure adopted is demonstrated with the design examples given below.

### 3.1 DESIGN EXAMPLE

#### Example1. Laterally Supported Beam

An ISJC 100 section is used as a beam over a span of 1 m, with simply supported ends. Determine the maximum factored uniformly distributed load that the beam can carry if the ends are restrained against torsion but compression flange is laterally supported.

#### Solution:

For ISJC 150, [11]

$$h = 100 \text{ mm}, t_w = 3 \text{ mm}, Z_e = 24800 \text{ mm}^3, Z_p = 28380 \text{ mm}^3$$

#### Design capacity of the section

$$M_d = \beta_b Z_p f_y / \gamma_{m0}$$

$$= (1.0 \times 28380 \times 250) / 1.1 = 6450000 \text{ N-mm}$$

$$\leq 1.2 Z_e f_y / \gamma_{m0} \leq (1.2 \times 24800 \times 250) / 1.1 = 6763636 \text{ N-mm}$$

#### Design Factored load

$$W = 8 * M_d / l^2 = (8 * 6450000) / (1000 * 1000) = 51.60 \text{ kN/m}$$

#### Design shear strength

$$V_d = (f_y * h * t_w) / (sq(3) * \gamma_{m0}) = (250 * 100 * 3) / (sq(3) * 1.1)$$

$$= 39364.8 \text{ N}$$

#### Check for $V < 0.6 V_d$

$$\text{Shear force } V = W * L / 2 = (51.60 * 1000) / 2 = 25800 \text{ N}$$

$$0.6 V_d = 0.6 * 39364.8 = 23618.9 \text{ N, Hence } V > 0.6 V_d$$

$$\beta = (2V / V_d - 1)^2 = [(2 * 25800) / 23618.9 - 1]^2 = 0.10$$

$$Z_{fd} = Z_p - A_w * Y_w$$

$$= (28380 - ((100 * 3 * 100) / 4)) = 20880 \text{ mm}^3$$

$$M_{fd} = (Z_{fd} * f_y) / \gamma_{m0} = (20880 * 250) / 1.1 = 4745455 \text{ N-mm}$$

$$M_{dv} = M_d - \beta (M_d - M_{fd}) = 1.2 Z_e f_y / \gamma_{m0}$$

$$= 6450000 - 0.1 * (6450000 - 4745455) = 6285330 \text{ N-mm}$$

$$W = 8 * M_{dv} / l^2 = (8 * 6285330) / (1000 * 1000) = 50.28 \text{ kN/m}$$

The design charts have been prepared effective span (mm) Vs Factored load (kN/m) based on the above example.

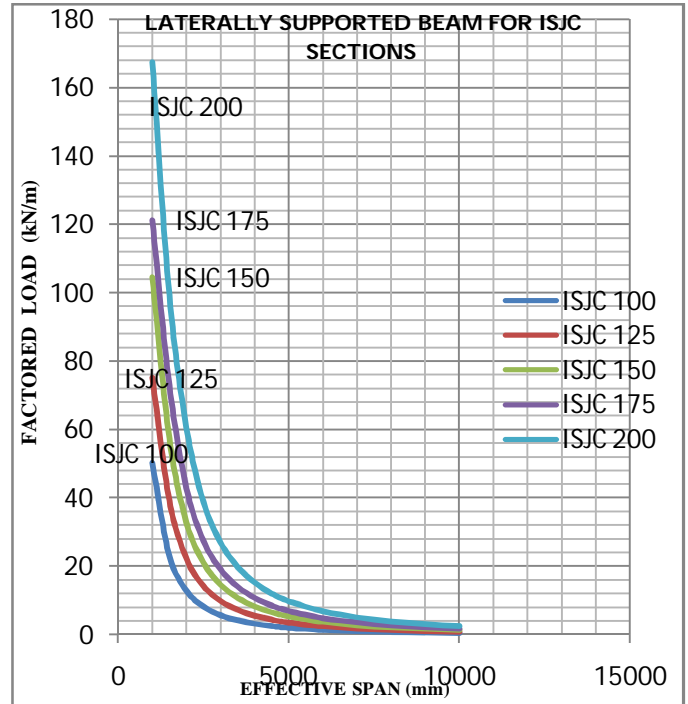


Fig.1 Graph is plotted factored load Vs effective span for ISJC.

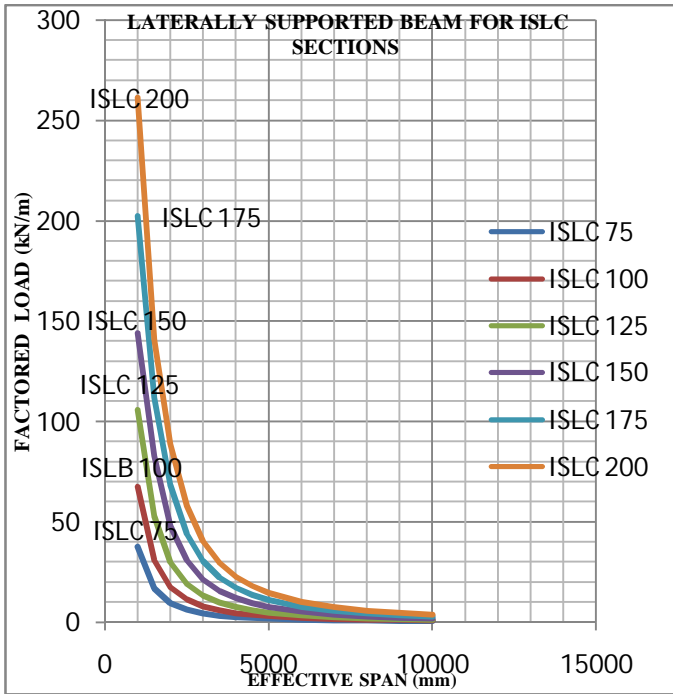


Fig.2 Graph is plotted factored load Vs effective span for ISLC.

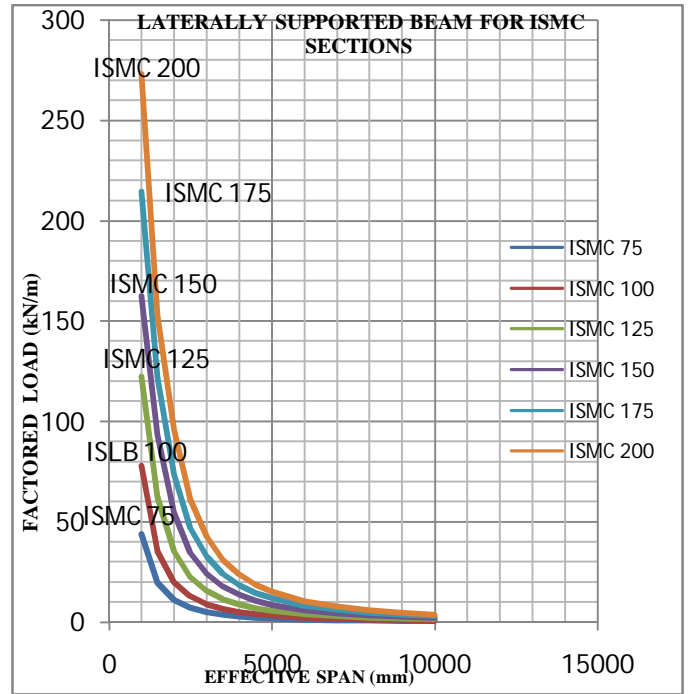


Fig.4 Graph is plotted factored load Vs effective span for ISMC.

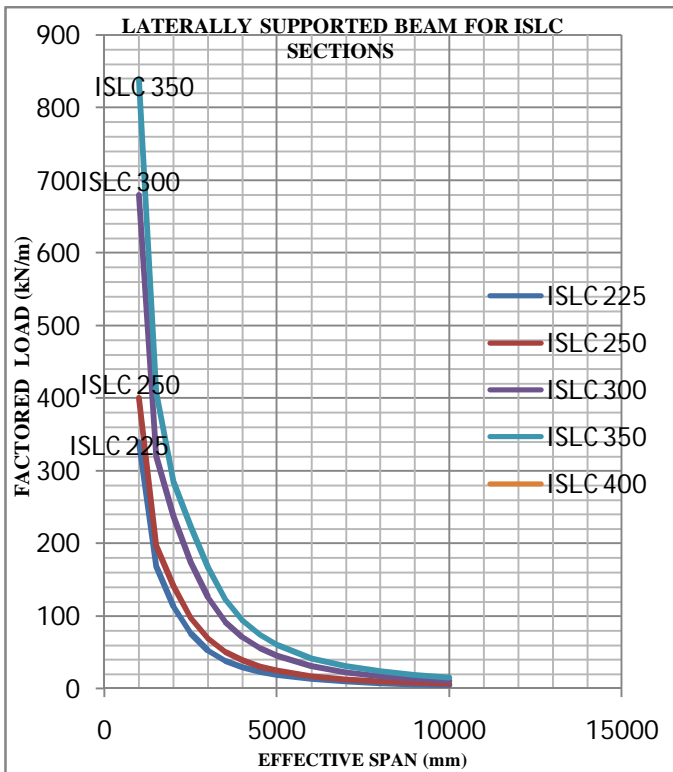


Fig.3 Graph is plotted factored load Vs effective span for ISLC.

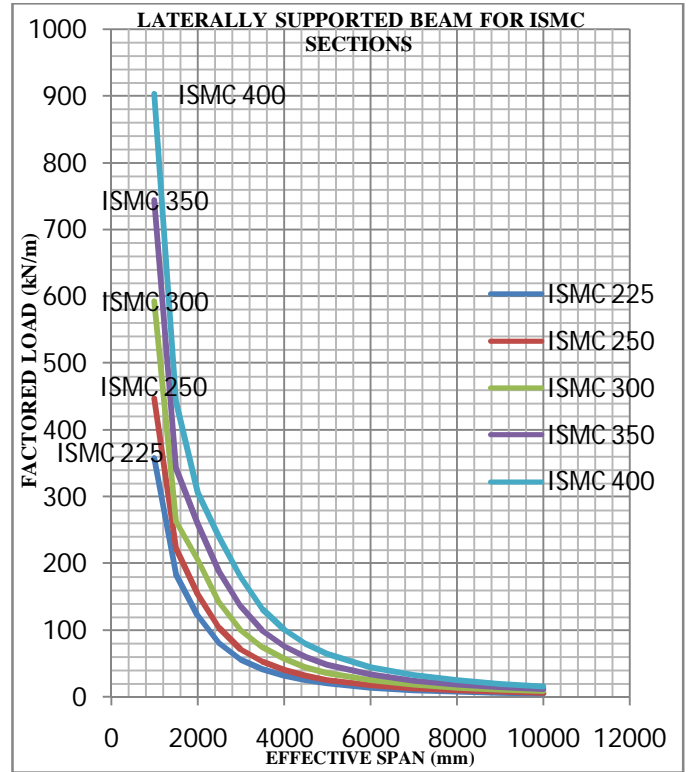


Fig.5 Graph is plotted factored load Vs effective span for ISMC.

**Example2. Laterally Unsupported Beam**

An ISJC 100 section is used as a beam over a span of 1 m, with simply supported ends. Determine the maximum factored uniformly distributed load that the beam can carry if the ends are restrained against torsion but compression flange is laterally unsupported.

**Solution:**

For ISJC 100[11]

$h = 100 \text{ mm}$ ,  $t_f = 5.1 \text{ mm}$ ,  $t_w = 3 \text{ mm}$ ,  
 $r_{yy} = 14.2 \text{ mm}$ , Effective length = 6 m.  
Area = 741 mm<sup>2</sup>  
 $KL/r = (1 \times 1000) / 14.2 = 70.42$   
 $h/t = 100/5.1 = 19.60$

**From Table 14 of IS 800: 2007**

$f_{crb}$  values as shown below:

h/t	18	19.60	20
KL/r			
70	587.4	X	562.9
70.42	.....	M	
80	478.4	Y	455.3

To get the value for  $h/t = 19.60$  and

$KL/r = 70.42$  it needs double linear interpolation

**First get the values at X and Y corresponding to  $h/t = 19.60$**

**To get the value at X ( $KL/r = 70$ ,  $h/t_f = 19.60$ )**

$$f_{crb} = 587.4 - 1.60/2 (587.4 - 562.9) = 567.704 \text{ N/mm}^2$$

**To get the value at Y ( $KL/r = 80$ ,  $h/t_f = 19.60$ )**

$$f_{crb} = 478.4 - 1.60/2 (478.4 - 455.3) = 459.83 \text{ N/mm}^2$$

∴ The value of  $f_{crb}$  at  $h/t_f = 19.60$  and  $KL/r = 70.42$ .

**To get the value at M.**

$$f_{crb} = 567.704 - 0.42/10 (567.704 - 459.83) = 563.145 \text{ N/mm}^2$$

**Referring to Table 13(a) in IS 800-2007, for  $f_y = 250 \text{ N/mm}^2$ ,**

We find  $f_{bd} = 188.6 \text{ N/mm}^2$  for  $f_{crb} = 500$ .

And  $f_{bd} = 197.7 \text{ N/mm}^2$  for  $f_{crb} = 600$ .

$$\therefore \text{ For } f_{crb} = 563.145$$

$$f_{bd} = 188.6 + 63.145/100(197.7 - 188.6) = 194.3 \text{ N/mm}^2$$

Hence it belongs to class 2 (compact) category.

$$\therefore M_d = \beta_b Z_p f_{bd}$$

$$\beta_b = 1, Z_p = 28380 \text{ mm}^3, f_{bd} = 194.3 \text{ N/mm}^2$$

$$\therefore M_d = 1 \times 28380 \times 194.3 = 5.515 \text{ kN-m}$$

If udl  $w$  is in kN/m, then  $WL^2/8 = M_d$

$$W \times 1^2/8 = 5.515 \Rightarrow W = 44.12 \text{ kN/m.}$$

The design charts have been prepared effective span (mm) Vs Factored load (kN/m) based on the above example.

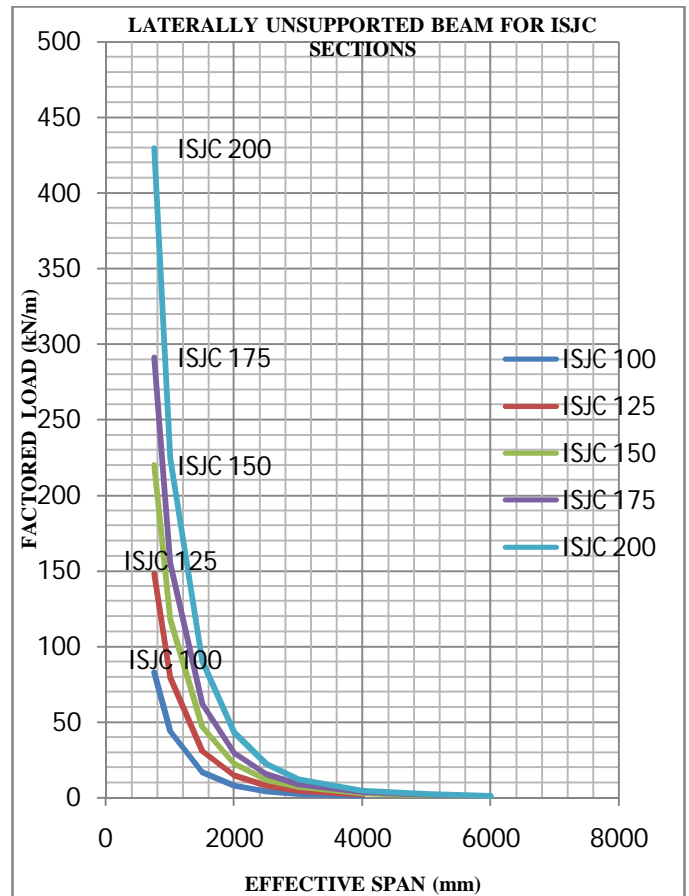


Fig.6 Graph is plotted for factored load Vs effective span.

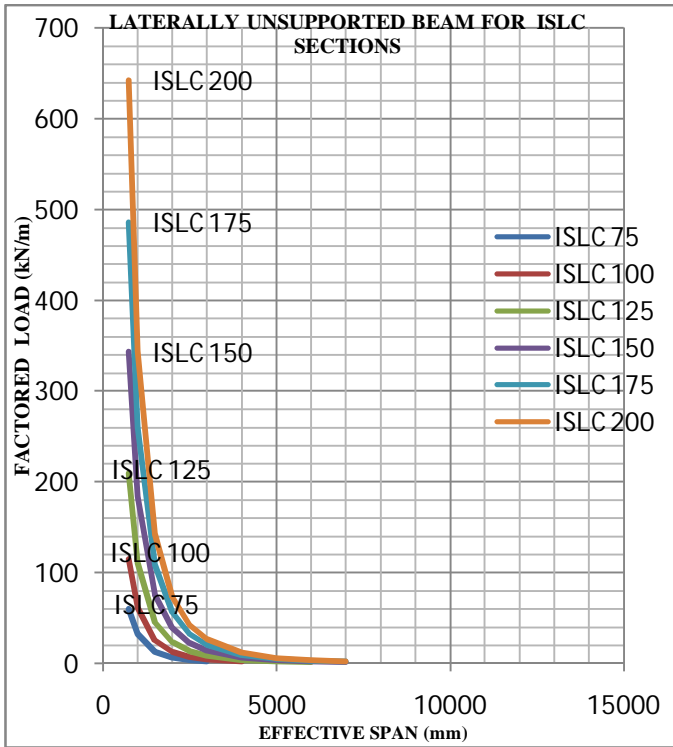


Fig.7 Graph is plotted for factored load Vs effective span.

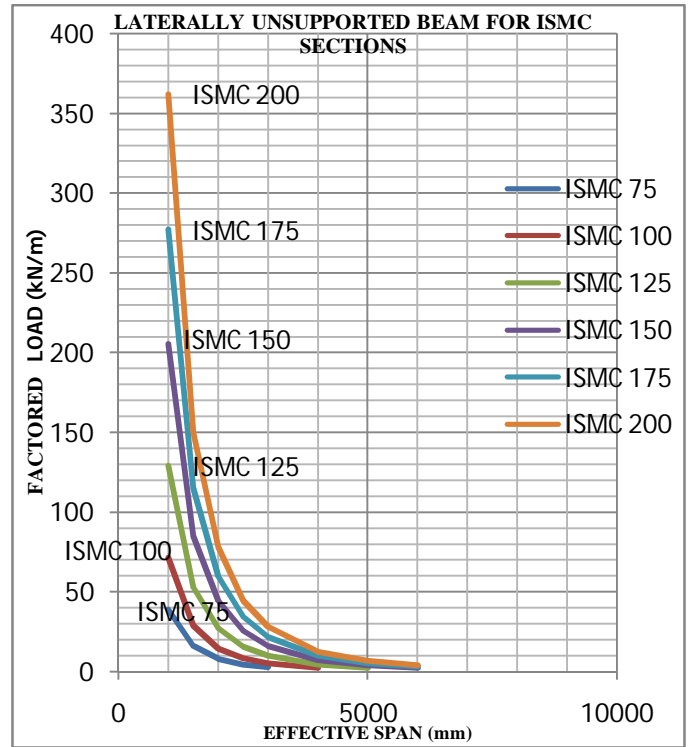


Fig.9 Graph is plotted for factored load Vs effective span.

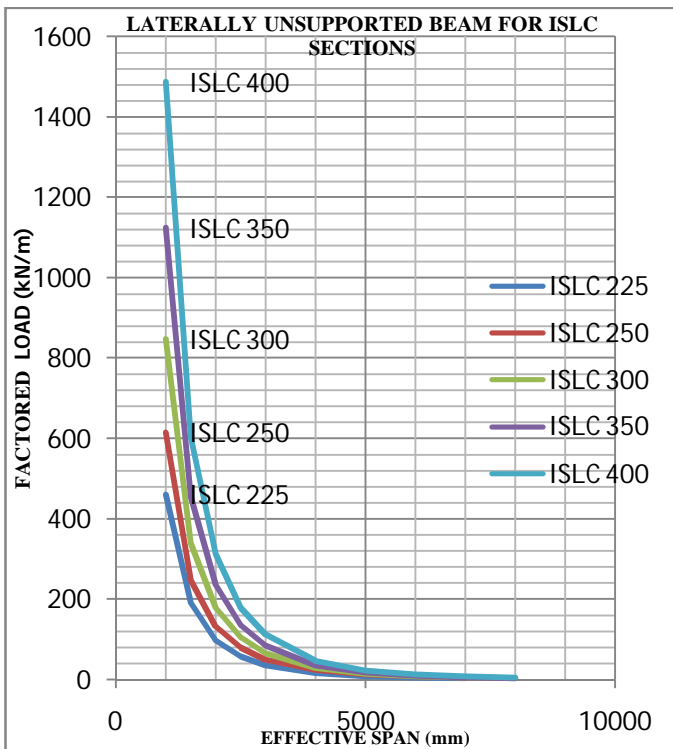


Fig.8 Graph is plotted for factored load Vs effective span.

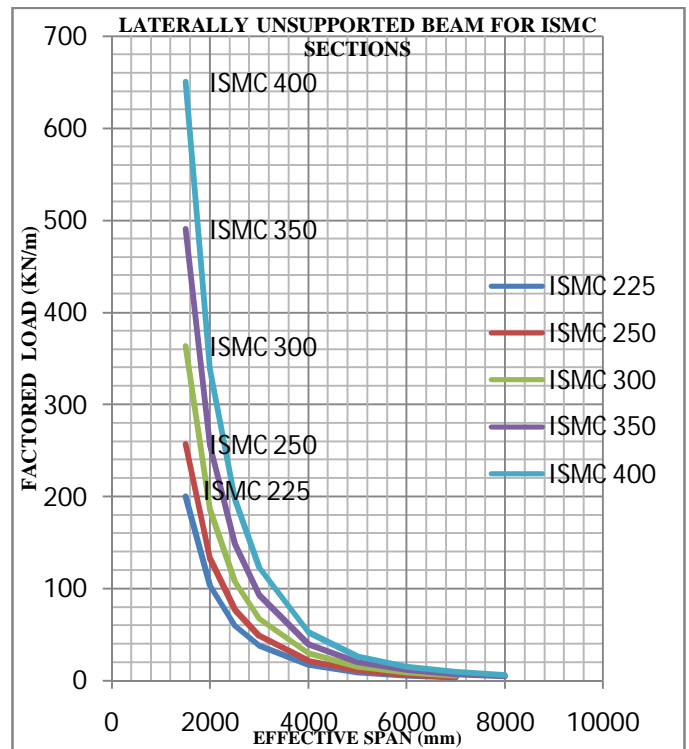


Fig.10 Graph is plotted for factored load Vs effective span.

#### 4. Design Charts for Beam-columns:

The Charts have been prepared based on IS: 800-2007 for beam-columns. The procedure adopted is demonstrated with the design example given below.

##### 4.1 DESIGN EXAMPLE

###### Example1. Beam-Column

An ISJC 100 section is used as a beam column of length 1m, with flexible joints. Determine the maximum factored axial load that the beam-column can carry safely.

###### **Solution:**

For ISJC 100 [11]

$h = 100 \text{ mm}$ ,  $t_f = 5.1 \text{ mm}$ ,  $t_w = 3 \text{ mm}$ ,

$r_{yy} = 14.2 \text{ mm}$ , Effective length = 6 m.

Area = 741 mm<sup>2</sup>

$KL/r = (1 \times 1000) / 14.2 = 70.42$

$h/t = 100/5.1 = 19.60$

###### From Table 14 of IS 800: 2007

$f_{crb}$  values as shown below:

h/t	18	19.60	20
KL/r			
70	587.4	X	562.9
70.42	.....	M	
80	478.4	Y	455.3

To get the value for  $h/t = 19.60$  and

$KL/r = 70.42$  it needs double linear interpolation

First get the values at X and Y corresponding to  $h/t = 19.60$

To get the value at X ( $KL/r = 70$ ,  $h/t_f = 19.60$ )

$f_{crb} = 587.4 - 1.60/2 (587.4 - 562.9) = 567.704 \text{ N/mm}^2$

To get the value at Y ( $KL/r = 80$ ,  $h/t_f = 19.60$ )

$f_{crb} = 478.4 - 1.60/2 (478.4 - 455.3) = 459.83 \text{ N/mm}^2$

∴ The value of  $f_{crb}$  at  $h/t_f = 19.60$  and  $KL/r = 70.42$ .

To get the value at M.

$f_{crb} = 567.704 - 0.42/10 (567.704 - 459.83) = 563.145 \text{ N/mm}^2$

Referring to Table 13(a) in IS 800, for  $f_y = 250 \text{ N/mm}^2$ ,

We find  $f_{bd} = 188.6 \text{ N/mm}^2$   $f_{crb} = 500$ .

And  $f_{bd} = 197.7 \text{ N/mm}^2$  for  $f_{crb} = 600$ .

∴ For  $f_{crb} = 563.145$

$f_{bd} = 188.6 + 63.145/100(197.7 - 188.6) = 194.3 \text{ N/mm}^2$

Hence it belongs to class 2 (compact) categories.

∴  $M_d = \beta_b Z_p f_{bd}$

$\beta_b = 1$ ,  $Z_p = 28380 \text{ mm}^3$ ,  $f_{bd} = 194.3 \text{ N/mm}^2$

∴  $M_{dz} = 1 \times 28380 \times 194.3 = 5.5155 \text{ kN-m}$

Member buckling resistance in compression (clause 7.1.2)

Minor axis buckling, using curve (c)

From Table 9c of the code, for  $KL/r = 70.42$  and  $f_y = 250 \text{ N/mm}^2$

70	152
70.42	.....
80	136

$f_{cr} = 152 - 0.42/10 (152 - 136) = 151.33 \text{ N/mm}^2$

$P_{dy} = N_d = f_{cr} * A$

$N_d = (151.33 * 741) / 1000 = 112.13 \text{ kN}$

We have calculated  $N_d$  and  $M_d$  for ISJC 100. Now the Design factored axial load  $N$  is calculated by increasing factored moment  $M$  in the equation no.(4). The design charts have been prepared Factored moment (kN/m) Vs Factored axial load (kN) for different effective span based on the above example.

#### 4.2 Design Charts for all ISJC sections.

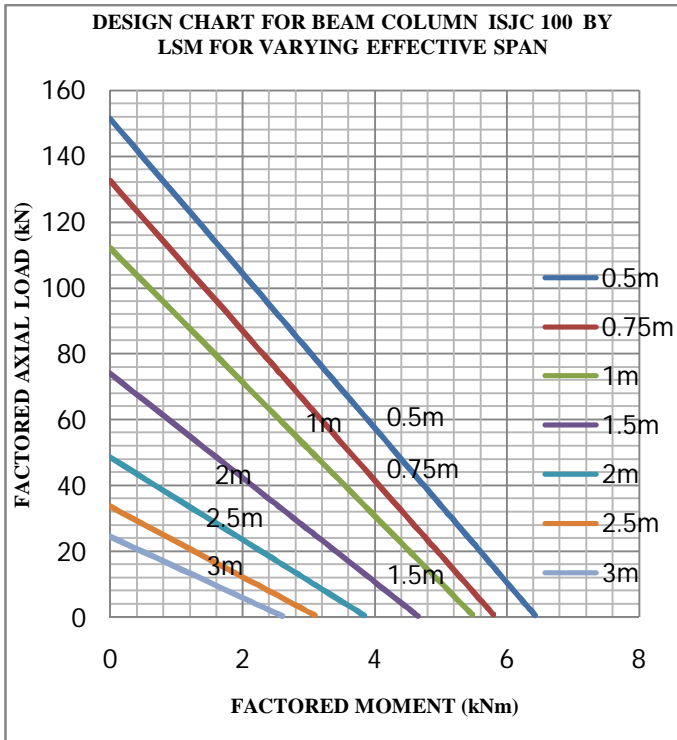


Fig.11 Graph is plotted for Factored Axial Load Vs Factored Moment for ISJC 100.

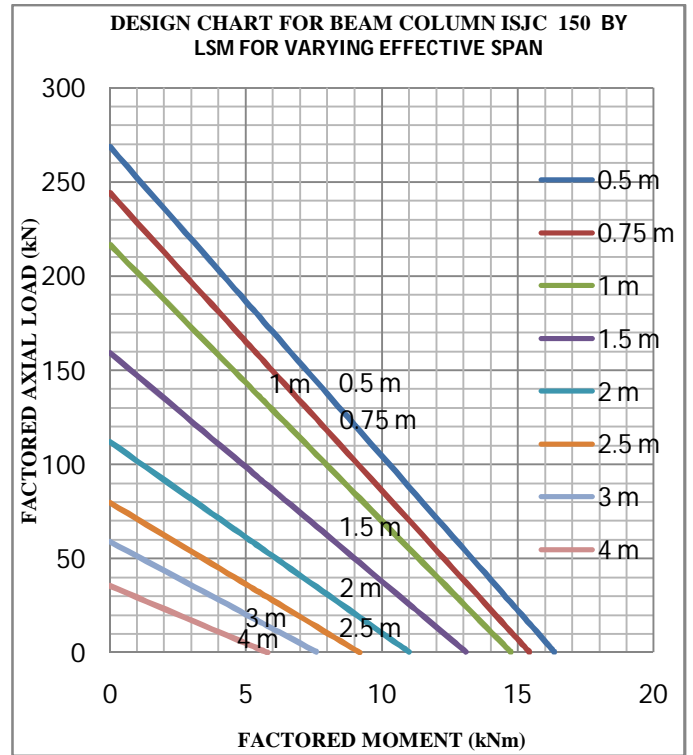


Fig.13 Graph is plotted for Factored Axial Load Vs Factored Moment for ISJC 150.

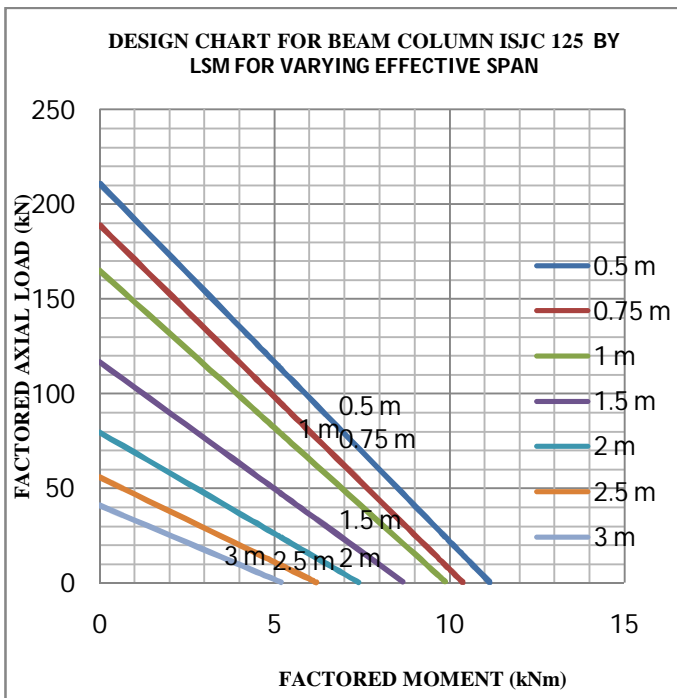


Fig.12 Graph is plotted for Factored Axial Load Vs Factored Moment for ISJC 125.

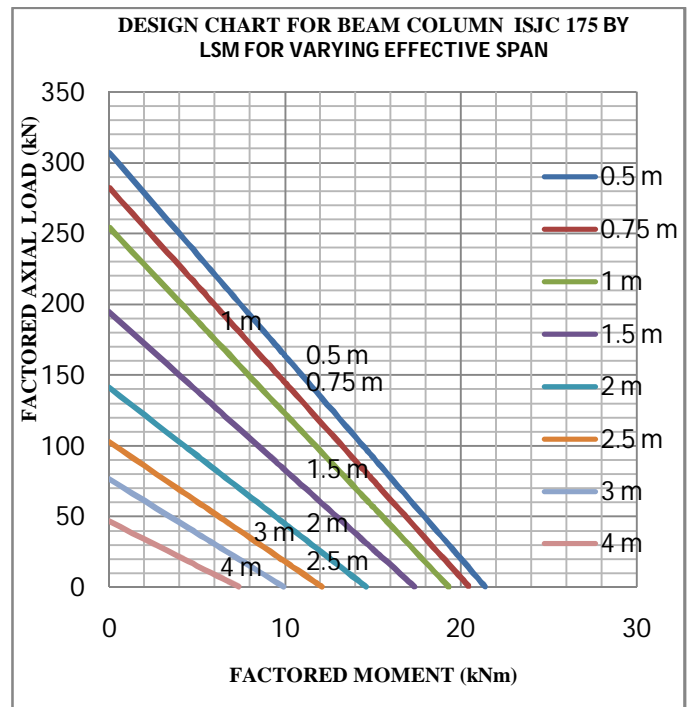


Fig.15 Graph is plotted for Factored Axial Load Vs Factored Moment for ISJC 175.



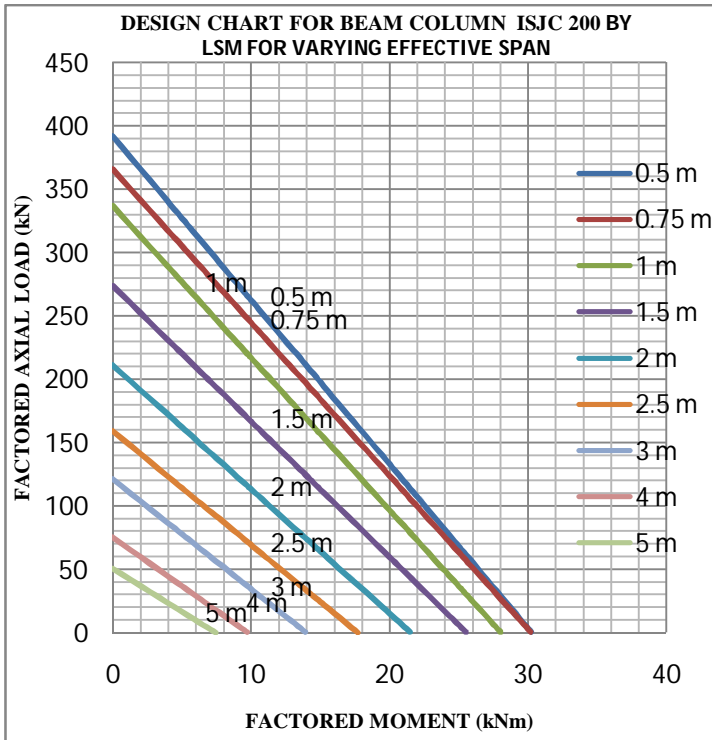


Fig.14 Graph is plotted for Factored Axial Load Vs Factored Moment for ISJC 200.

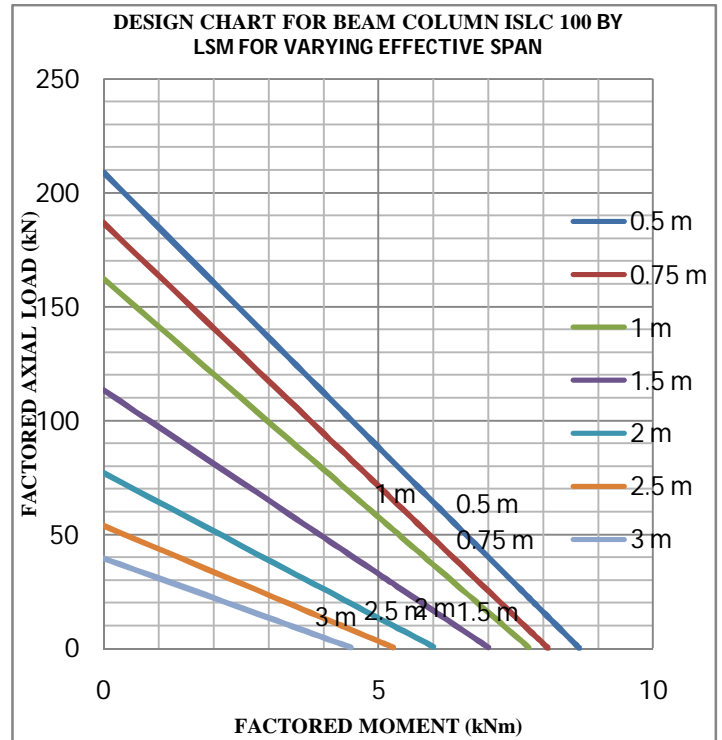


Fig.17 Graph is plotted for Factored Axial Load Vs Factored Moment for ISLC 100.

**4.3 Design Charts for all ISLC sections**

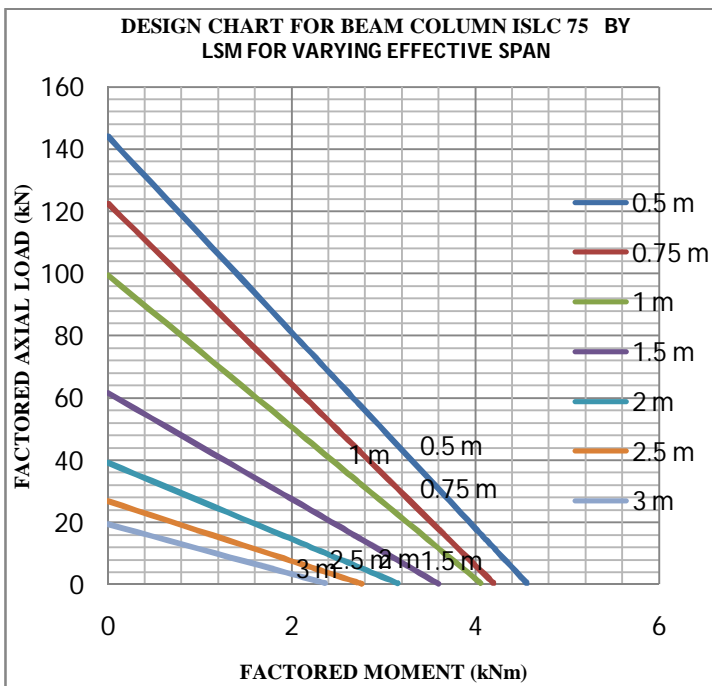


Fig.16 Graph is plotted for Factored Axial Load Vs Factored Moment for ISLC 75.

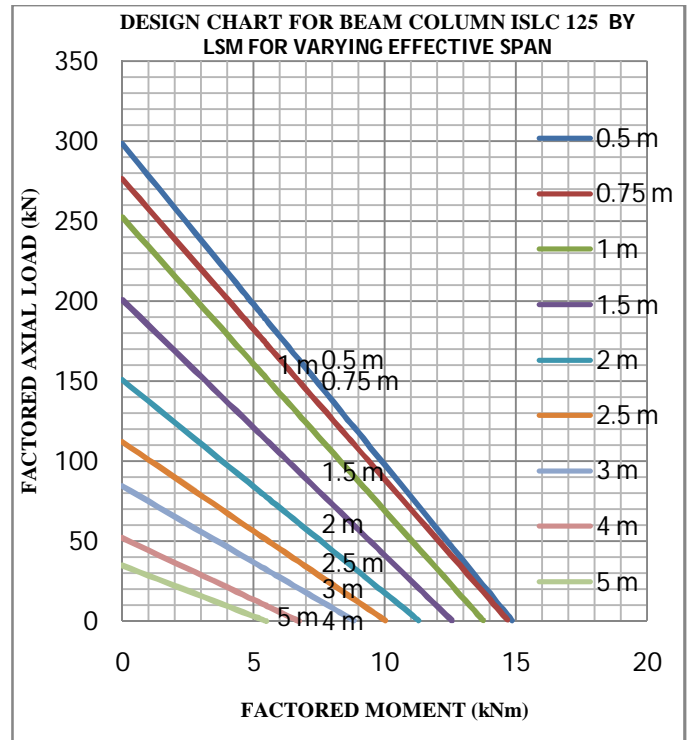


Fig.18 Graph is plotted for Factored Axial Load Vs Factored Moment for ISLC 125.

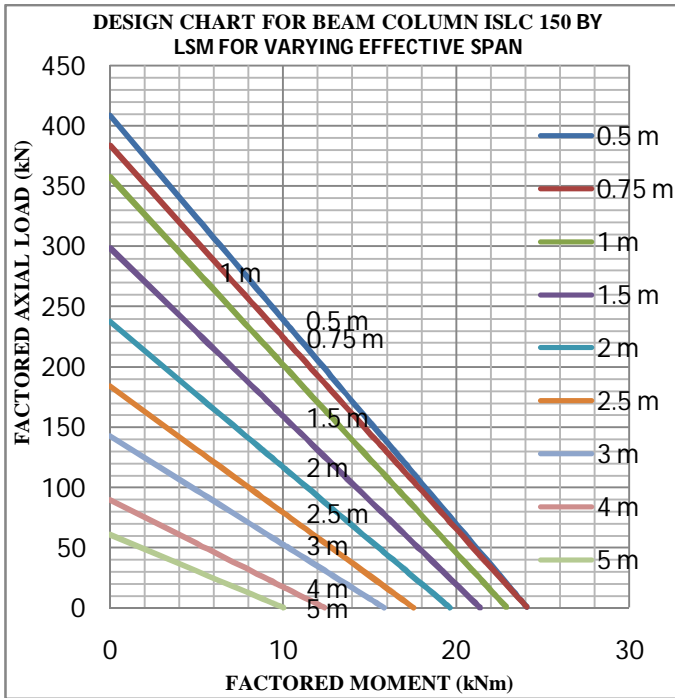


Fig.19 Graph is plotted for Factored Axial Load Vs Factored Moment for ISLC 150.

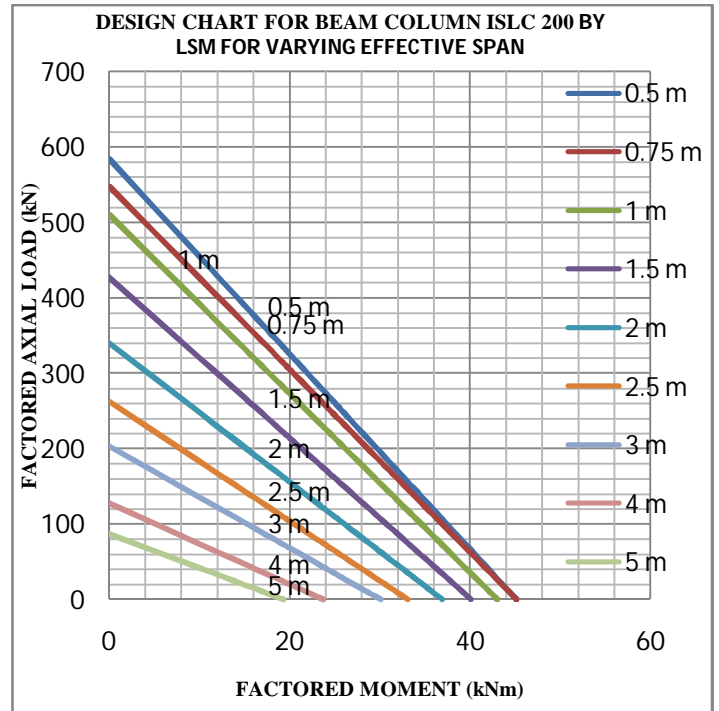


Fig.21 Graph is plotted for Factored Axial Load Vs Factored Moment for ISLC 200.

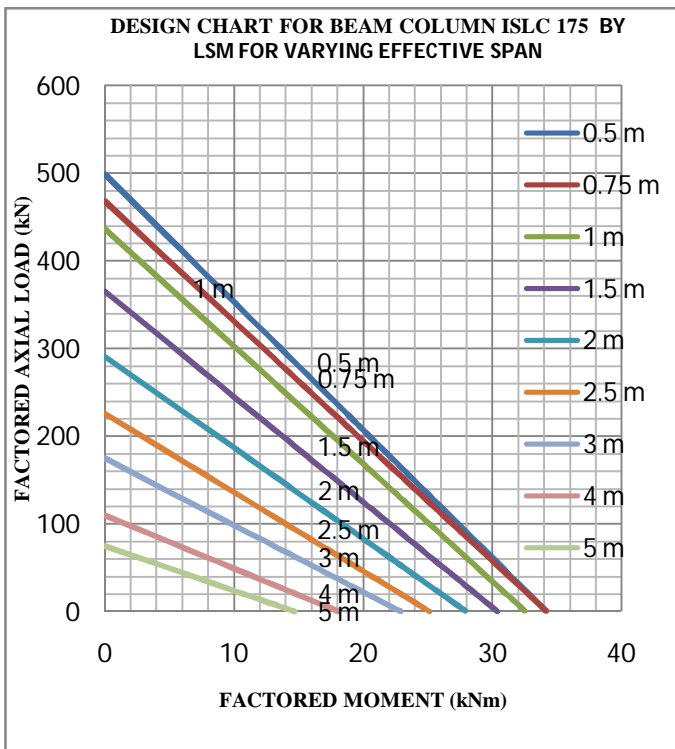


Fig.20 Graph is plotted for Factored Axial Load Vs Factored Moment for ISLC 175.

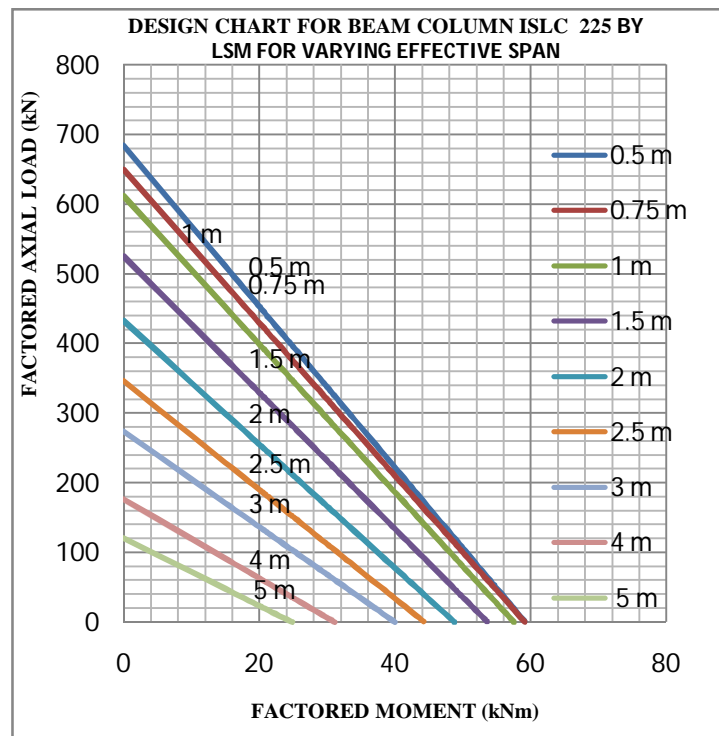


Fig.22 Graph is plotted for Factored Axial Load Vs Factored Moment for ISLC 225.

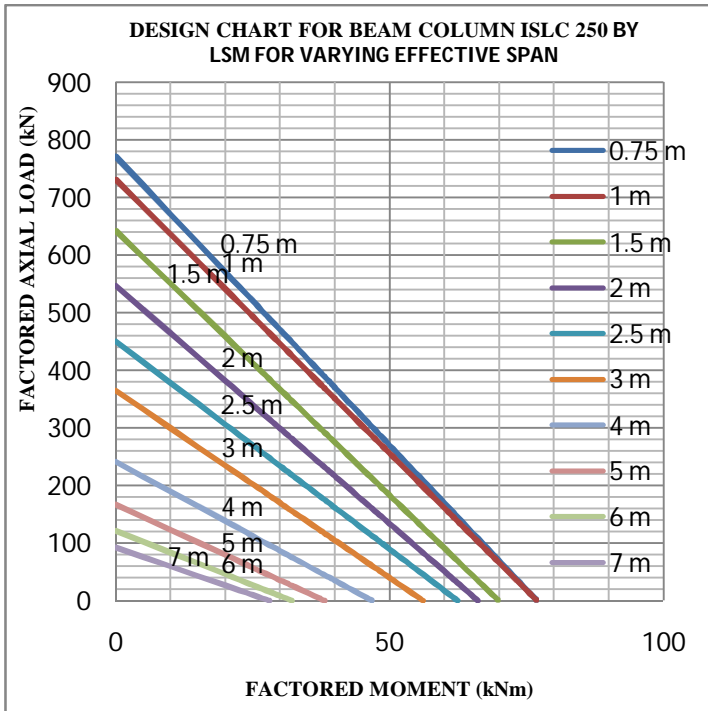


Fig.23 Graph is plotted for Factored Axial Load Vs Factored Moment for ISLC 250.

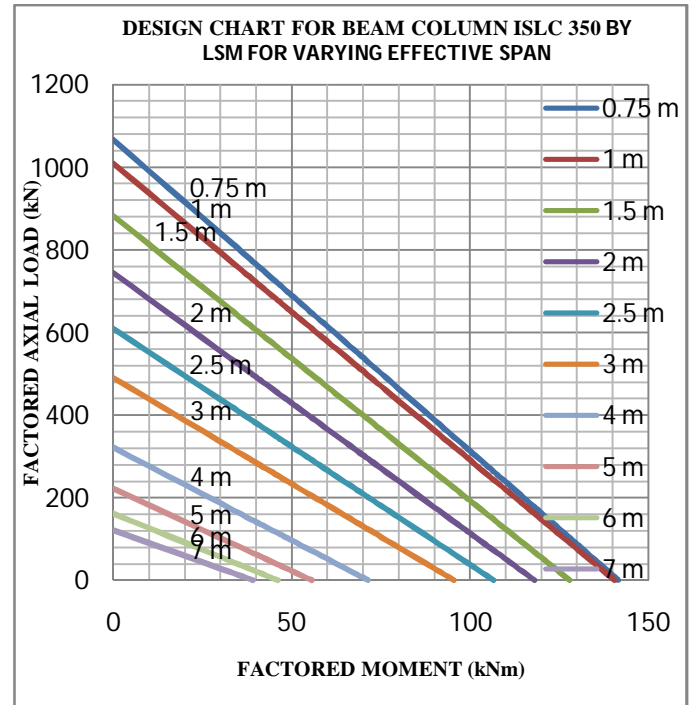


Fig.25 Graph is plotted for Factored Axial Load Vs Factored Moment for ISLC 350.

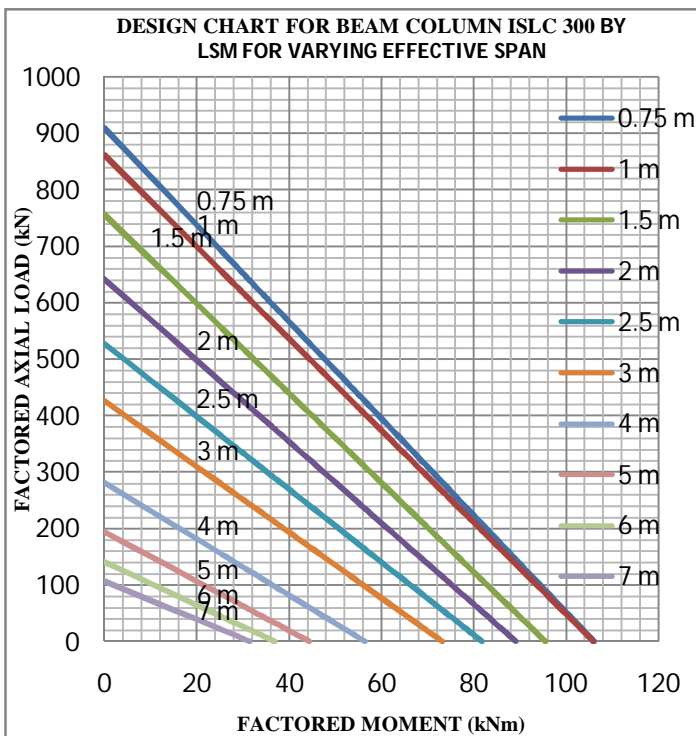


Fig.24 Graph is plotted for Factored Axial Load Vs Factored Moment for ISLC 300.

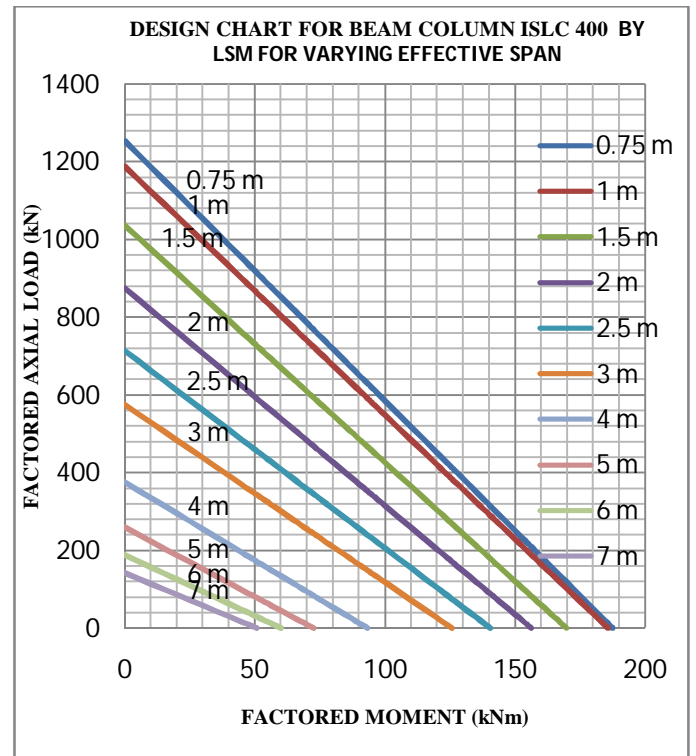


Fig.26 Graph is plotted for Factored Axial Load Vs Factored Moment for ISLC 400.

4.4 design Charts for all ISMC sections

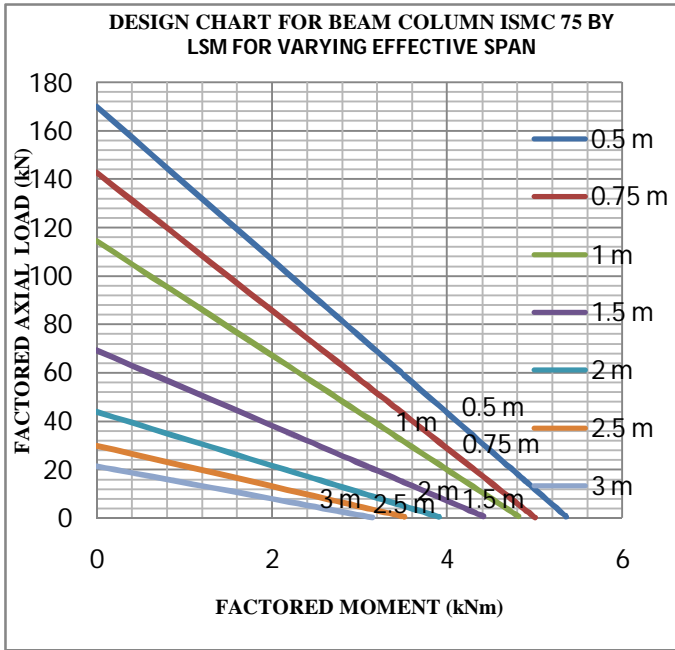


Fig.27 Graph is plotted for Factored Axial Load Vs Factored Moment for ISMC 75.

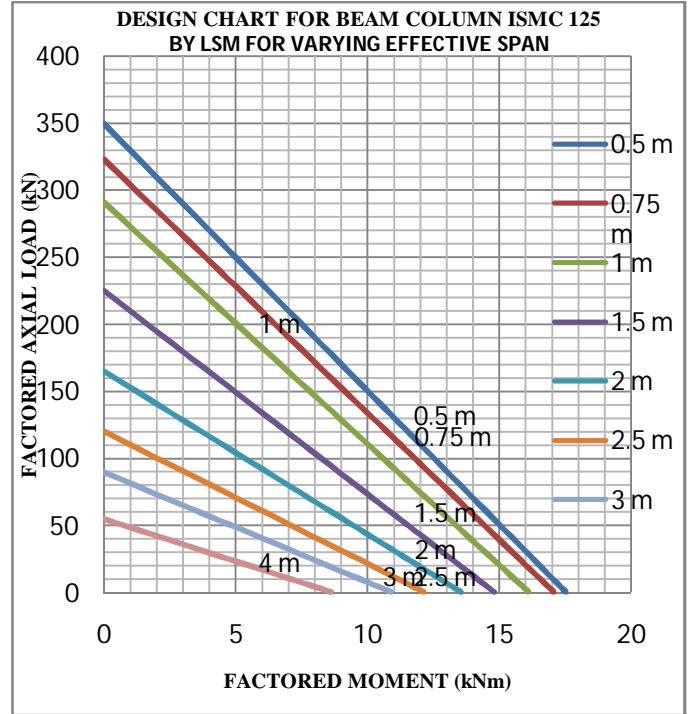


Fig.29 Graph is plotted for Factored Axial Load Vs Factored Moment for ISMC 125.

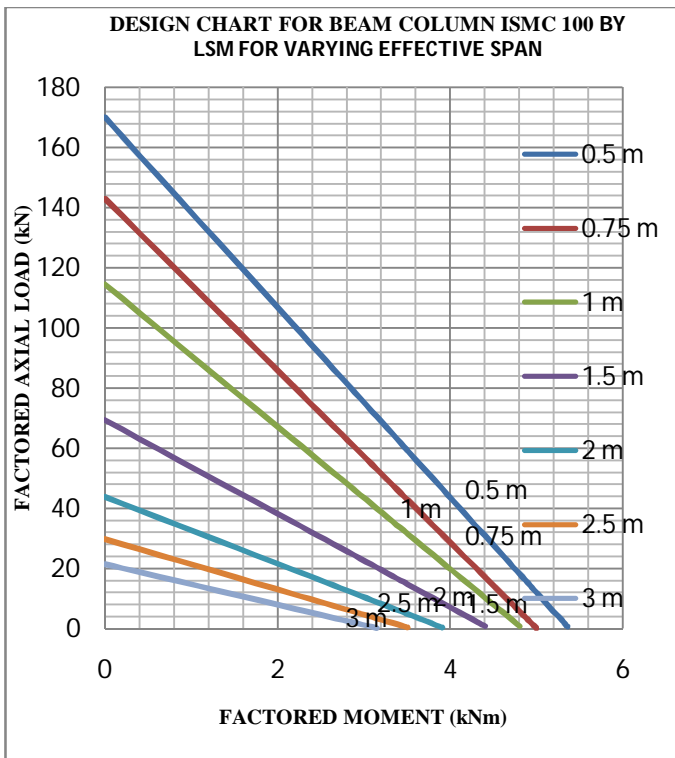


Fig.28 Graph is plotted for Factored Axial Load Vs Factored Moment for ISMC 100.

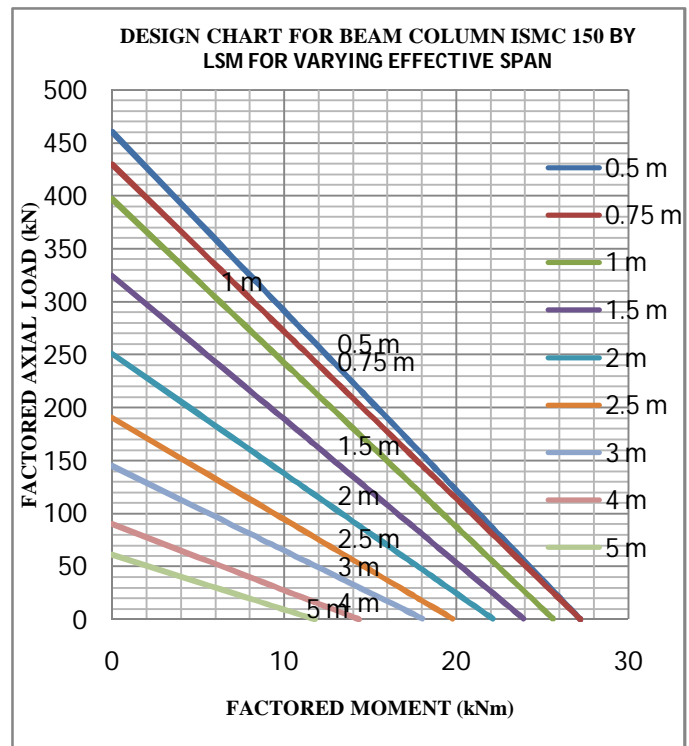


Fig.30 Graph is plotted for Factored Axial Load Vs Factored Moment for ISMC 150.

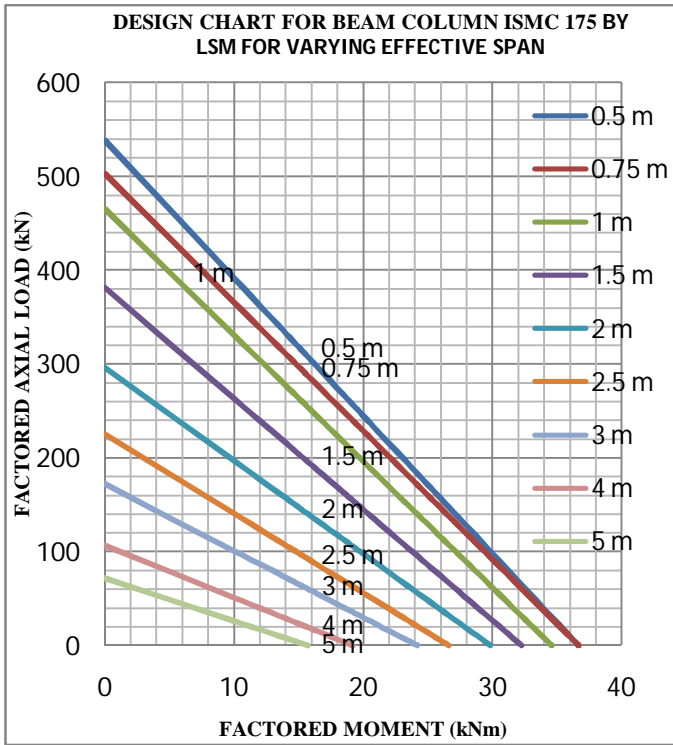


Fig.31 Graph is plotted for Factored Axial Load Vs Factored Moment for ISMC 175.

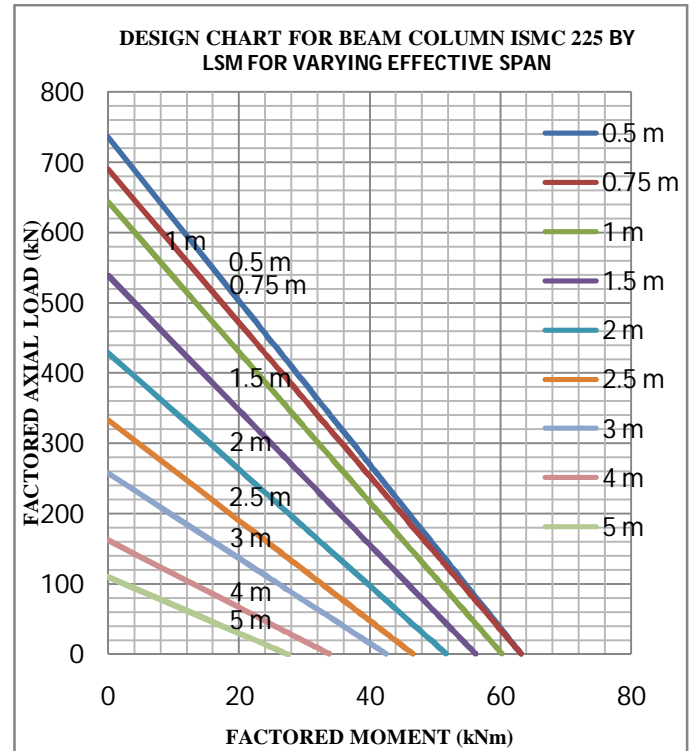


Fig.33 Graph is plotted for Factored Axial Load Vs Factored Moment for ISMC 225.

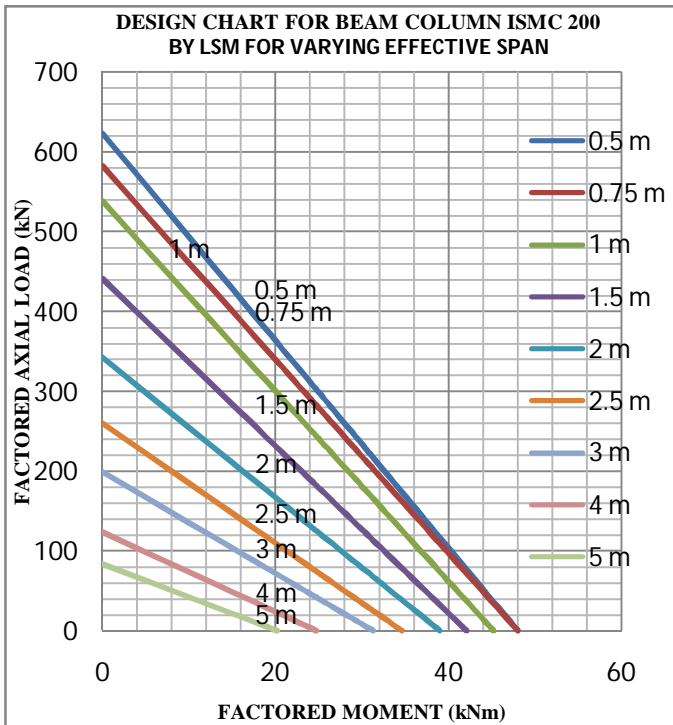


Fig.32 Graph is plotted for Factored Axial Load Vs Factored Moment for ISMC 200.

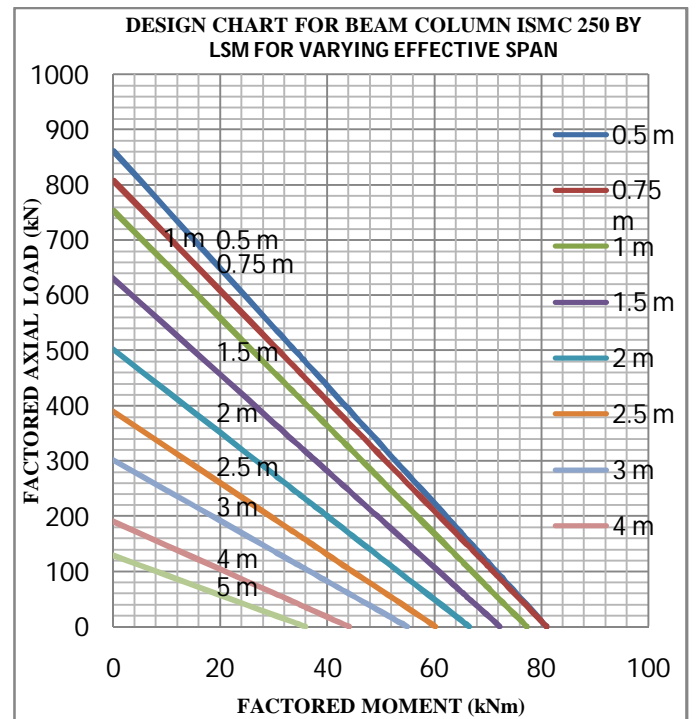


Fig.34 Graph is plotted for Factored Axial Load Vs Factored Moment for ISMC 250.

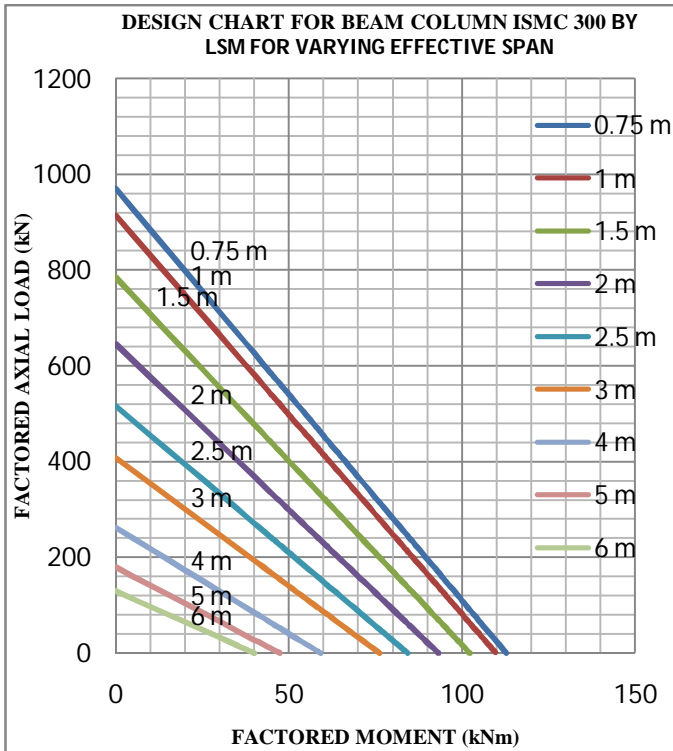


Fig.35 Graph is plotted for Factored Axial Load Vs Factored Moment for ISMC 300.

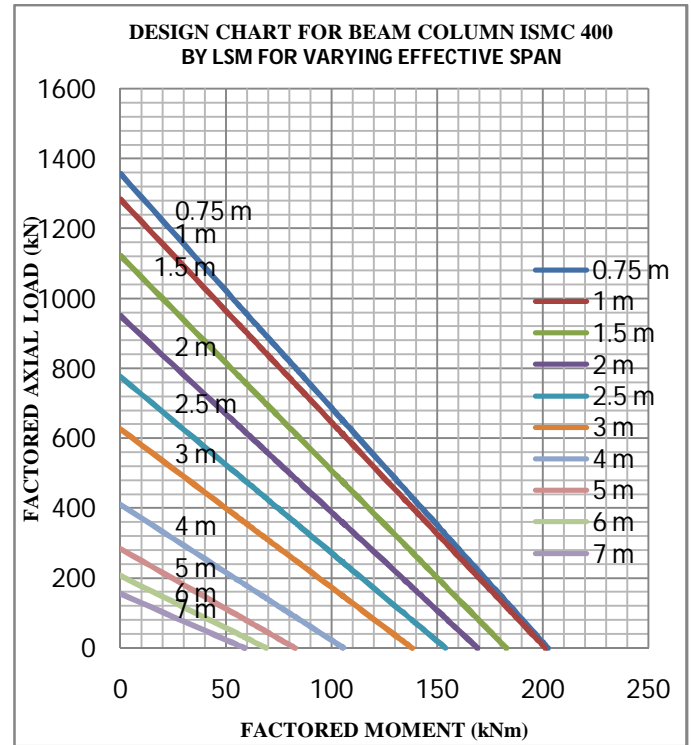


Fig.37 Graph is plotted for Factored Axial Load Vs Factored Moment for ISMC400.

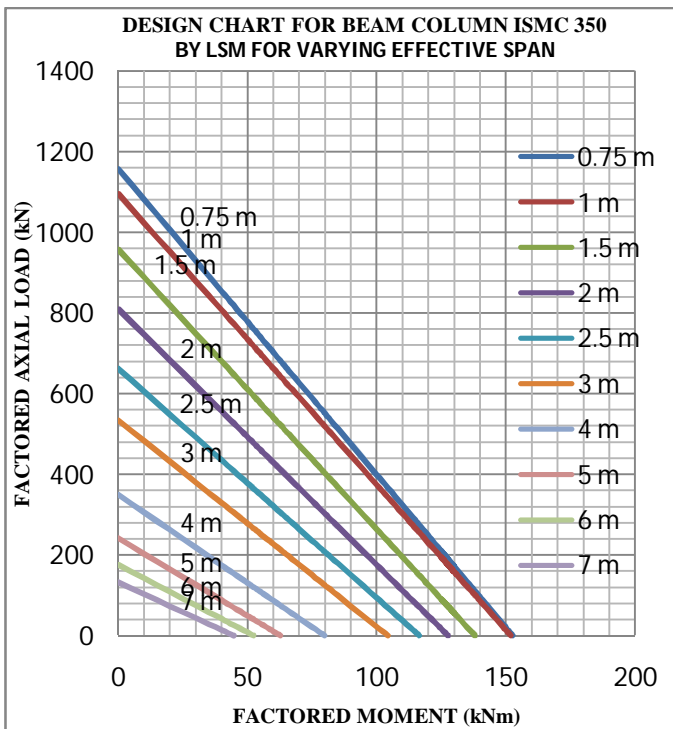


Fig.36 Graph is plotted for Factored Axial Load Vs Factored Moment for ISMC 350.

## 5. DESIGN USING CHARTS

### 5.1 Flexural member ( Laterally Supported Beam )

A beam carries factored Load is 50kN/m and the effective span 2m design the suitable channel section.

Select the suitable section for the above load and span

From fig 1. Select ISJC 175.

From fig 2. Select ISLC 150.

From fig 4. Select ISMC 150.

### 5.2 Flexural member ( Laterally Unsupported Beam )

A beam carries factored Load is 50kN/m and the effective span 2m and the beam is laterally unsupported design the section.

Select the suitable section for the above load and span

From fig 6. ISJC section are not suitable.

From fig 7. Select ISLC 175.

From fig 9. Select ISMC 150.

### 5. 3 Beam-Column

A simply supported beam supports 50kN/m factored lateral load for an effective span of 3m. The beam is also subjected to factored axial load of 300kN. Select a suitable section.

Factored axial load = 300kN

Factored moment =  $(50 \times 3 \times 3) / 8 = 56.25$  kNm

From fig 26. Select ISLC 400 (factored axial load 300kN and factored moment 60kNm)

From fig 37. select ISMC 400 (factored axial load 300kN and factored moment 70kNm)

### 6. CONCLUSION

Design charts for the design of steel sections made up of Indian standard channel sections. These design charts are presented based on IS: 800-2007.

The graphs have been prepared for the flexural members (Laterally Supported and Unsupported) channel sections, which can be used to select the section directly for different effective span and the factored load (kN/m), the member can with stand. These graphs can be used as designed aids for selecting steel sections.

In case of Beam-Columns (channel sections), the design aid graphs are prepared for the factored axial load against factored moment which is a sloping straight line for different effective spans.

#### NOTATIONS

- A** = section area.
- A<sub>g</sub>** = gross area of cross section in mm<sup>2</sup>.
- E** = modulus of elasticity.
- F<sub>rb</sub>** = elastic critical buckling stress.
- f<sub>bd</sub>** = design bending compressive stress.
- f<sub>y</sub>** = characteristic yield strength.

- I** = minimum moment of inertia.
- KL** = effective length of the member.
- KL/r** = effective slenderness ratio of the section.
- L** = actual length of column, beam.
- M<sub>d</sub>** = design bending strength of the section.
- M<sub>dv</sub>** = design bending strength under high shear.
- M<sub>fd</sub>** = plastic design strength of the area of the cross section excluding the shear area, considering partial safety factor  $\gamma_{mo}$ .
- P<sub>d</sub>** = critical buckling load.
- r** = appropriate radius of gyration.
- t<sub>w</sub>** = thickness of the web.
- t<sub>f</sub>** = thickness of flange .
- V** = factored applied shear force as governed by web yielding or web buckling.
- V<sub>d</sub>** = shear strength as governed by web yielding or web buckling.
- Z** = elastic section moduli of the cross-section.
- Z<sub>e</sub>** = Elastic Section modulus.
- Z<sub>p</sub>** = Plastic Section modulus.
- γ<sub>mo</sub>** = the partial safety factor for failure in tension by yielding.
- γ<sub>mt</sub>** = partial safety factor for failure at ultimate stress.
- λ** = non-dimensional effective slenderness ratio.
- χ<sub>Lt</sub>** = bending stress reduction factor to account for lateral torsional buckling.

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