Lateral Torsional Buckling: how to deal with it

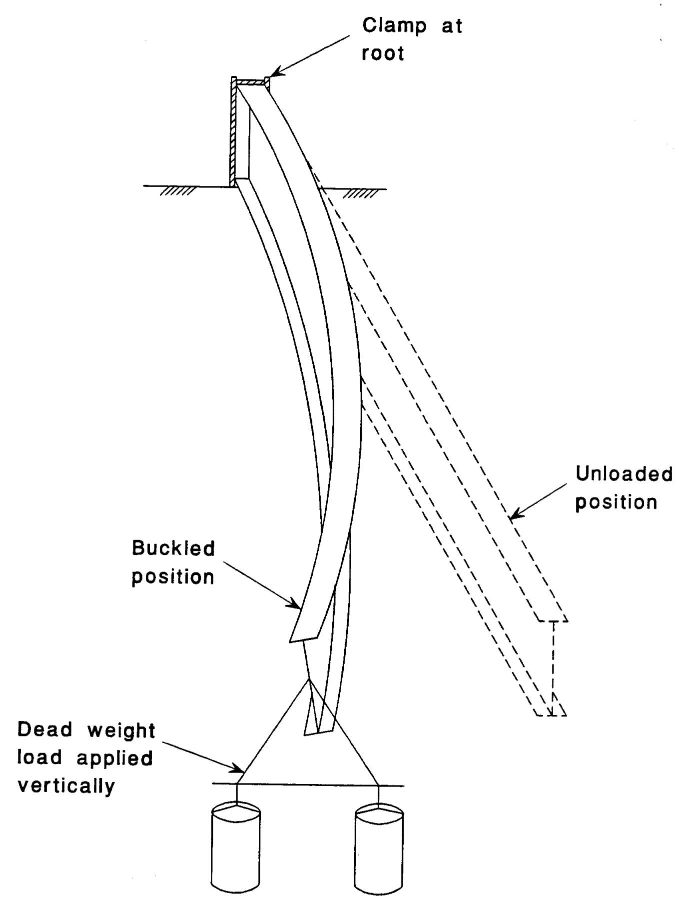
Yong Wang
Professor of Structural and Fire Engineering,
University of Manchester

Outline of contents

- Introduction to lateral torsional buckling (LTB)
- Requirements for effective lateral restraints
- Examples to show effects of effective lateral restraints (reduced LTB length) by stringers
- Using friction underneath to provide effective lateral restraints – would this be sufficient?
- Way forward
- Conclusions and important messages

Introduction to LTB

- Out-of-plane movement & twist under in-plane loading
- Due to low out-of-plane stiffness & long buckling length
- Buckling length = physical length between effective lateral restraints
- Worse for deeper/narrower beams



MANCHESTER 1824
The University of Manchester

Basics of LTB (Eurocode 3)

$$M_{b,Rd} = \chi_{LT} W_{pl,y} f_y / \gamma_{M1}$$

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}^2}} \text{ but } \chi \le 1. \quad \phi = 0.5\left[1 + \alpha\left(\bar{\lambda} - 0.2\right) + \bar{\lambda}^2\right]$$

$$\bar{\lambda} = \sqrt{\frac{Af_y}{N_{cr}}} = \frac{\lambda}{\lambda_1}, \ \lambda = \frac{L_e}{r}, \lambda_1 = \pi\sqrt{E / f_y} = 93.9\varepsilon$$

$$\lambda_{LT} = 0.9 \frac{L_{LT} / i_z}{\sqrt{C_1}}$$

MANCHESTER 1824
The University of Manchester

Effectiveness of possible lateral restraints in offshore structure

- Grating: not effective due to low strength and disintegration in fire
- Steel stringers: some (e.g. every two or three) could be engineered not to fail in fire so as to provide effective lateral restraint, but needs to demonstrate effectiveness of such.
- Pipes: deserves further exploration either on its own as effective restraint or as part of restraint system including steel stringers

MANCHESTER 1824
The University of Manchester

MANCHESTER
1824
The University of Manchester

Requirements for effective lateral restraint

ULTIMATE STRENGTH ANALYSIS OF THREE DIMENSIONAL STRUCTURES WITH FLEXIBLE RESTRAINTS

BY

Wang Yong Chang

(B.Sc)

A Thesis Submitted to the University of Sheffield for the Degree of Doctor of Philosophy

June, 1988

The University of Manchester

Bracing requirements

A brief parametric study has been performed by using a rigorous finite-element program to address the problem of bracing requirements for unrestrained beams. It is concluded that, for a single-bracing system, 1% of the axial force in a flange at failure may be taken as the bracing-strength requirement in design. For multiple-bracing systems, this value may be unsafe in certain cases, especially for beams with high slenderness. However, a value of 2% may be considered more appropriate as a total figure, with a maximum value of 1% for each brace.

J. Construct. Steel Research **17** (1990) 305–315

Bracing Requirements for Laterally Unrestrained Beams*

Y. C. Wang

Department of Civil and Structural Engineering, University of Sheffield, Sheffield, UK

&

D. A. Nethercot

Department of Civil Engineering, University of Nottingham, Nottingham, UK

Illustrative examples to demonstrate the benefits of lateral restraints in fire, if restraint effects are not included in cold design

If lateral restraints are provided by stringers …

Ratio of LTB/plastic resistances

533x210x122	122.0	544.5	211.9	12.7	21.3	12.7	476.5	4.97	37.5	76040	3388	22.1	4.67
533x210x109	109.0	539.5	210.8	11.6	18.8	12.7	476.5	5.61	41.1	66820	2943	21.9	4.60
533x210x101	101.0	536.7	210.0	10.8	17.4	12.7	476.5	6.03	44.1	61520	2692	21.9	4.57
533x210x92	92.1	533.1	209.3	10.1	15.6	12.7	476.5	6.71	47.2	55230	2389	21.7	4.51
533x210x82	82.2	528.3	208.8	9.6	13.2	12.7	476.5	7.91	49.6	47540	2007	21.3	4.38
457x191x98	98.3	467.2	192.8	11.4	19.6	10.2	407.6	4.92	35.8	45730	2347	19.1	4.33
457x191x89	89.3	463.4	191.9	10.5	17.7	10.2	407.6	5.42	38.8	41020	2089	19.0	4.29
457x191x82	82.0	460.0	191.3	9.9	16.0	10.2	407.6	5.98	41.2	37050	1871	18.8	4.23
457x191x74	74.3	457.0	190.4	9.0	14.5	10.2	407.6	6.57	45.3	33320	1671	18.8	4.20
457x191x67	67.1	453.4	189.9	8.5	12.7	10.2	407.6	7.48	48.0	29380	1452	18.5	4.12
457x152x82	82.1	465.8	155.3	10.5	18.9	10.2	407.6	4.11	38.8	36590	1185	18.7	3.37
457x152x74	74.2	462.0	154.4	9.6	17.0	10.2	407.6	4.54	42.5	32670	1047	18.6	3.33
457x152x67	67.2	458.0	153.8	9.0	15.0	10.2	407.6	5.13	45.3	28930	913	18.4	3.27
457x152x60	59.8	454.6	152.9	8.1	13.3	10.2	407.6	5.75	50.3	25500	795	18.3	3.23
457x152x52	52.3	449.8	152.4	7.6	10.9	10.2	407.6	6.99	53.6	21370	645	17.9	3.11
406x178x74	74.2	412.8	179.5	9.5	16.0	10.2	360.4	5.61	37.9	27310	1545	17.0	4.04
406x178x67	67.1	409.4	178.8	8.8	14.3	10.2	360.4	6.25	41.0	24330	1365	16.9	3.99
406x178x60	60.1	406.4	177.9	7.9	12.8	10.2	360.4	6.95	45.6	21600	1203	16.8	3.97
406x178x54	54.1	402.6	177.7	7.7	10.9	10.2	360.4	8.15	46.8	18720	1021	16.5	3.85
406x140x46	46.0	403.2	142.2	6.8	11.2	10.2	360.4	6.35	53.0	15690	538	16.4	3.03
406x140x39	39.0	398.0	141.8	6.4	8.6	10.2	360.4	8.24	56.3	12510	410	15.9	2.87
356x171x67	67.1	363.4	173.2	9.1	15.7	10.2	311.6	5.52	34.2	19460	1362	15.1	3.99
356x171x57	57.0	358.0	172.2	8.1	13.0	10.2	311.6	6.62	38.5	16040	1108	14.9	3.91
356x171x51	51.0	355.0	171.5	7.4	11.5	10.2	311.6	7.46	42.1	14140	968	14.8	3.86
356x171x45	45.0	351.4	171.1	7.0	9.7	10.2	311.6	8.82	44.5	12070	811	14.5	3.76
356x127x39	39.1	353.4	126.0	6.6	10.7	10.2	311.6	5.89	47.2	10170	358	14.3	2.68
356x127x33	33.1	349.0	125.4	6.0	8.5	10.2	311.6	7.38	51.9	8249	280	14.0	2.58
305x165x54	54.0	310.4	166.9	7.9	13.7	8.9	265.2	6.09	33.6	11700	1063	13.0	3.93
305x165x46	46.1	306.6	165.7	6.7	11.8	8.9	265.2	7.02	39.6	9899	896	13.0	3.90
305x165x40	40.3	303.4	165.0	6.0	10.2	8.9	265.2	8.09	44.2	8503	764	12.9	3.86
305x127x48	48.1	311.0	125.3	9.0	14.0	8.9	265.2	4.47	29.5	9575	461	12.5	2.74
305x127x42	41.9	307.2	124.3	8.0	12.1	8.9	265.2	5.14	33.1	8196	389	12.4	2.70
305x127x37	37.0	304.4	123.4	7.1	10.7	8.9	265.2	5.77	37.4	7171	336	12.3	2.67

MANCHESTER
1824
The University of Manchester

Effects of lateral restraints: example results

- 12m span, S355 steel
- min i_z~30mm
- Typically, i_z~45mm for beam depth/span ratio of 1/20, i.e. >500mm
- LTB resistance with effective restraints ~10 times without restraints, though LTB still governs

Iz		L(lt)	lambda	bar	phi	x
30	L(lt)	12000	360	4.768593	12.34944	0.042121
30	1/2L(lt)	6000	180	2.384296	3.571786	0.160481
30	1/3L(lt)	4000	120	1.589531	1.909205	0.337066
30		3000	90	1.192148	1.314784	0.534972
30		2000	60	0.794765	0.878276	0.798681
45	L(lt)	12000	240	3.179062	5.866019	0.092628
45	1/2L(lt)	6000	120	1.589531	1.909205	0.337066
45	1/3L(lt)	4000	80	1.059687	1.151736	0.623865
45		3000	60	0.794765	0.878276	0.798681
45		2000	40	0.529844	0.675001	0.914745

The University of Manchester

Critical temperatures (assuming maximum uniform heating)

$$\theta_{a,cr} = 39{,}19 \ln\left[\frac{1}{0{,}9674\,\mu_0^{3{,}833}} - 1\right] + 482$$

		Ratio of Re	Load ratio	Tcr
L(lt)	12000	1	0.7	525.7836
1/2L(lt)	6000	3.809997	0.183727	737.7518
1/3L(lt)	4000	8.002314	0.087475	849.2809
3000	3000	12.7008	0.055115	918.6733
2000	2000	18.96154	0.036917	978.8721
L(lt)	12000	1	0.7	525.7836
1/2L(lt)	6000	3.638934	0.192364	730.8402
1/3L(lt)	4000	6.735189	0.103932	823.3829
3000	3000	8.622481	0.081183	860.4941
2000	2000	9.875493	0.070883	880.8768

- If lateral restraints exist, and can be demonstrated to be effective, but the beneficial effects of lateral restraints have not been considered in cold design, then including the effects in fire design can greatly increase the critical temperature of steel, by >200C.
- With reduced risk of LTB, bending resistance of the bottom T becomes very important.

Can friction underneath pipes be effective restraints?

Calculations of friction: basis & results

- One set of pipes

M=(PD+PI).L/4

Nf=M/H=(PD+PI)/4.L/H

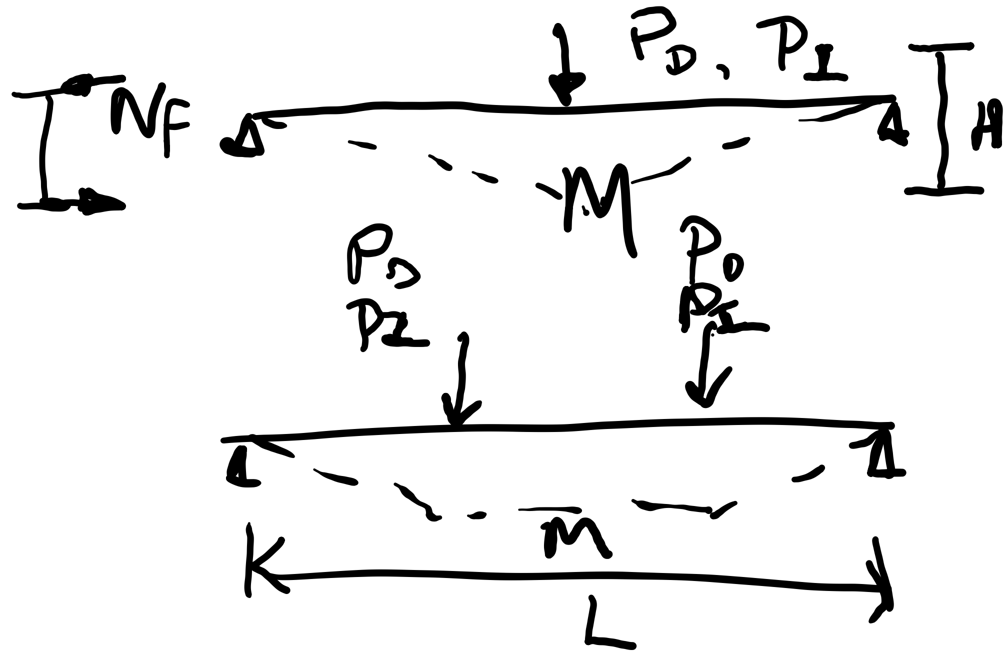
Fri=PI.(fric.coef)

Fri/Nf=PI/(PD+PI).4.coef.H
/L=2.(fric.coef.)*H/L= 0.02

(fric.coef=0.2, H/L=1/20,
PD=PI)

- Two sets of pipes

Replace 4 above by 3 for
each set of pipes, to give
0.015

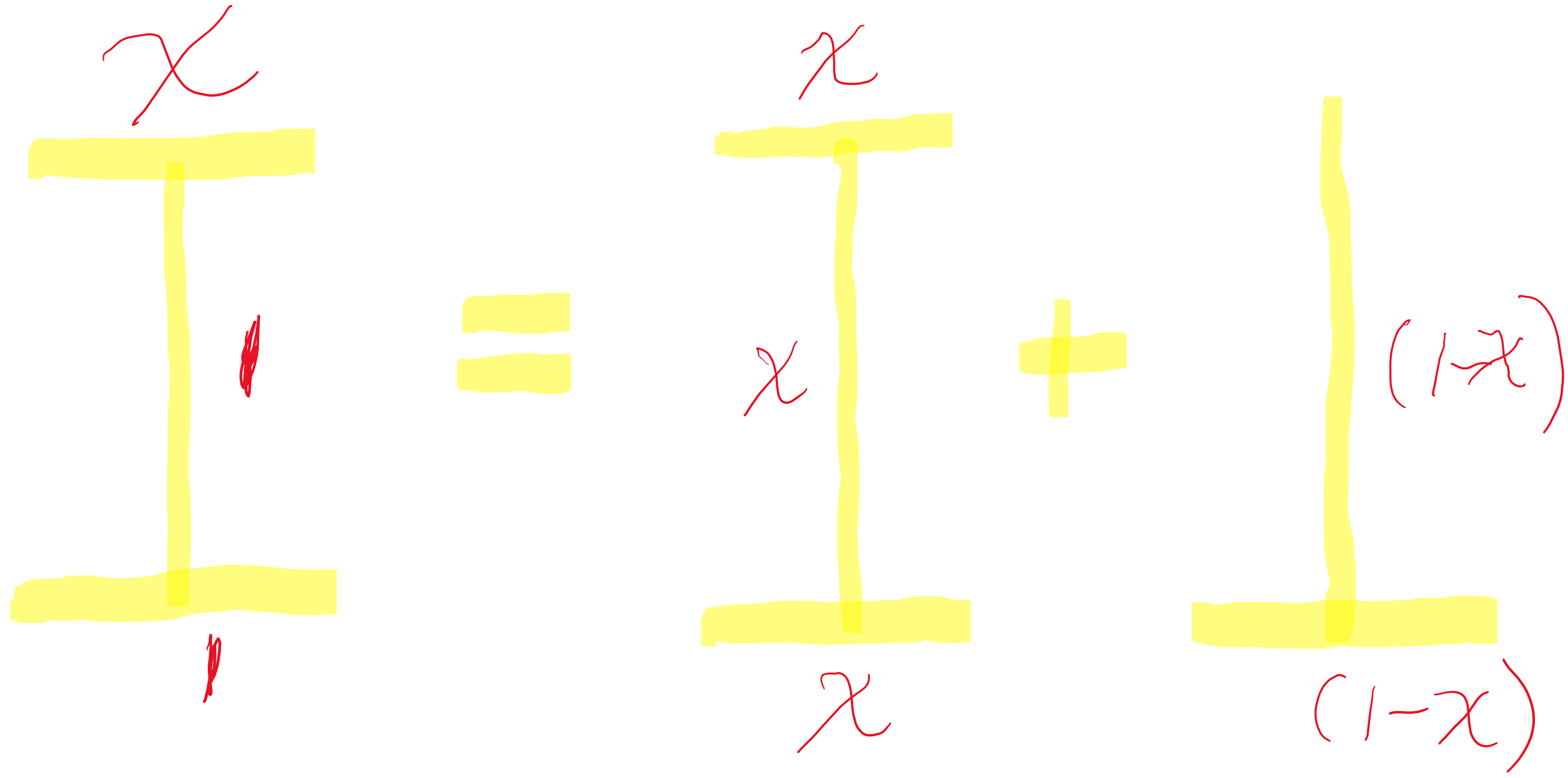


Effective lateral restraints

- Grating: unlikely to be useful – too weak in fire
- Stringers: effective if not fail in fire
- Pipes: likely effective if fully loaded

Examples - possible way forward

Basics



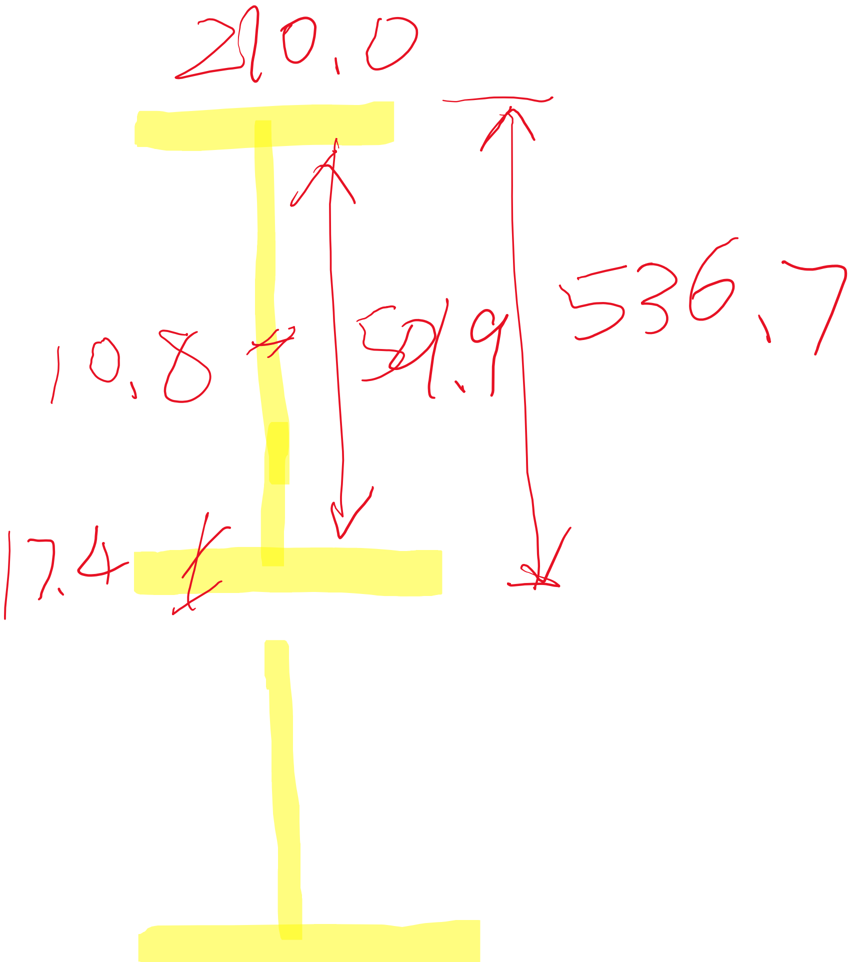
$$M_{3side} = x M_{4side} + (1-x) M_{\perp}$$

$$\frac{M_{3side}}{M_{4side}} = x + (1-x) \frac{M_{\perp}}{M_{4side}}$$

Say, 533x210x101UKB

$$\boxed{M = f_y W_{pl,y}}$$

$$W_{pl,y,I} = 2578\,cm^3$$



$$\frac{W_{pl,y,L}}{W_{pl,y,I}} = \frac{1133}{2578} = 0.44$$

If full LT restraints in cold and in fire:

4 side, T			3 side, Tbottom			
		800 (0.11)		900 (0.06)		1000 (0.04)
500		x=0.14		x=0.08		x=0.05
(0.78)		M3/M4=0.52		0.48		0.47
600		x=0.57		x=0.13		x=0.09
(0.47)		M3/M4=0.57		0.51		0.49
700		x=0.48		x=0.26		x=0.17
(0.23)		M3/M4=0.7		0.56		0.54

MANCHESTER 1824
The University of Manchester

Summary

Case 1: If full restraint in cold & in fire

- 3 side resistance = 0.5-0.7 resistance of 4 side,

Or

- 4 side resistance = 1.5-2 times resistance of 3 side

Case 2: If full restraint in cold, not LTB in fire

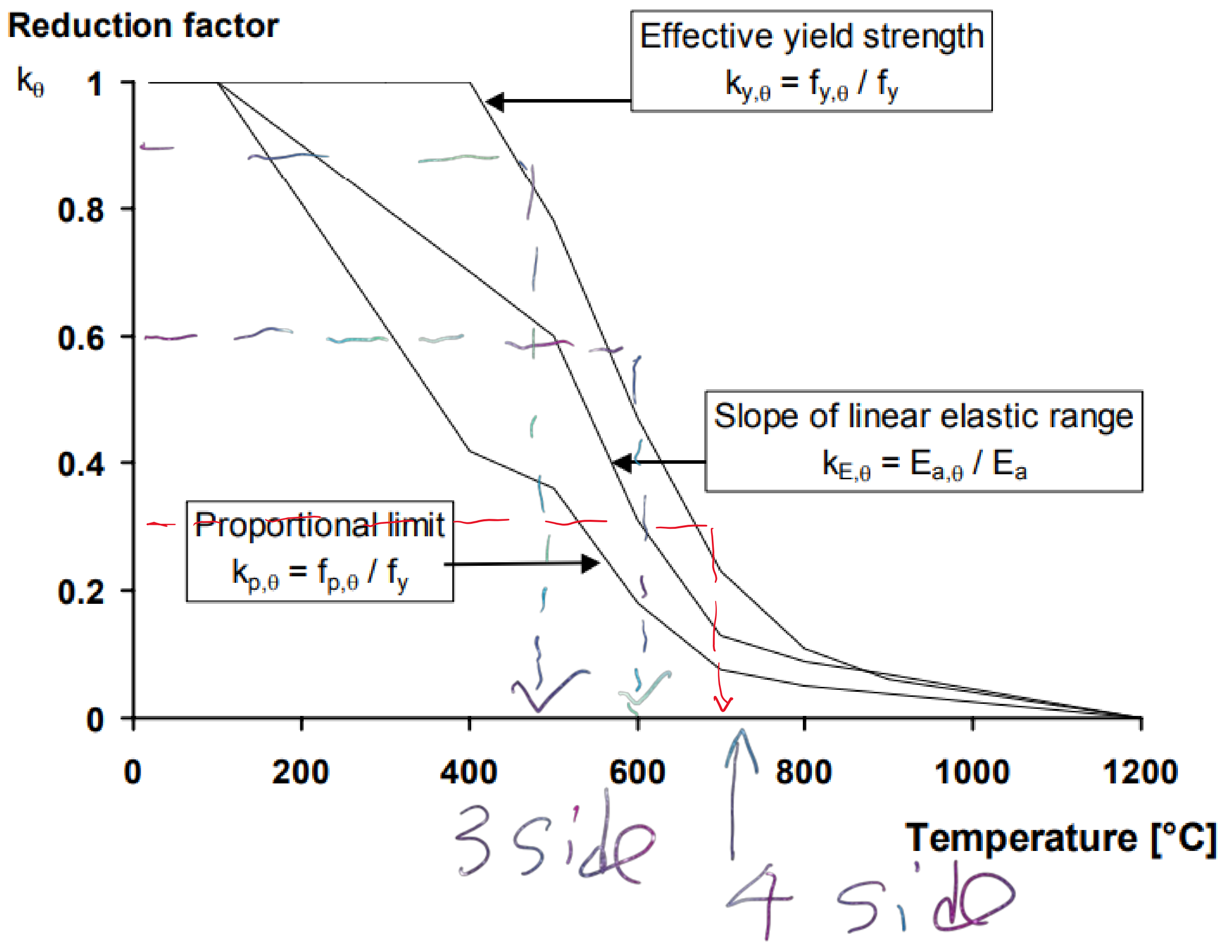
- Say LTB resistance = 0.7 full bending resistance
- 3 side resistance = 0.35-0.5 resistance of 4 side,

Or

- 4 side resistance = 2-3 times resistance of 3 side

Maximum load ratio for 3-side = maximum load ratio for 4-side * (1.5-2 for case 1 or 2-3 for case 2)

Range of decrease in limiting temperature



Summary of way forward

- Maximum resistance of 3 side = 0.5-0.7 (0.35-0.5) resistance of 4 side. So maximum applied load of 3 side = above factors * maximum applied load of 4 side.
- Design fire protection for 100~200 degrees lower limiting temperature than 4 side protection
- Ensure effective lateral restraints

MANCHESTER 1824

The University of Manchester

Main conclusions

- With out lateral restraints, LTB governs in failure, due to long span.
- If cold design to LTB resistance without taking advantage of lateral restraints, but fire design assumes effective restraints, critical temperature >200C higher than default Tcr.
- Possible engineering solutions

- Determine the stringers requiring protection to restrain the beam.
- Explore the effects of friction underneath pipes.
- Decrease applied load + increased fire protection

- Non-uniform heating in 3-sided protection beneficial, but not considered – important under bending failure.

Important message

- If cold design assumes bending resistance (no LTB), the effectiveness of lateral restraints must be demonstrated. Otherwise, there is great risk of inadequate structural resistance. Localised heating may be of beneficial, but requires further research.
- There is a possible forward, but further work is needed, e,g,

- calculation of LTB resistance for 3-sided protection

- demonstration of effectiveness of lateral restraints, especially pipe friction

- design optimisation (number of fully functional stringers)

- effects of localised fire exposure