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INFLUENCE OF FLANGE AND WEB ON LOCAL BUCKLING OF I SECTIONS UNDER BENDING

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Abstract. *Steel sections are usually classified as compact or slender according to their bending moment capacity relative to the plastic or yield moment. This is primarily done by considering the element slenderness (b/t) of the flange and the web against established limits. This paper reports on the results of finite element simulation of local buckling to assess the level of interaction between the flange and web when examining these limits. The results suggested that the impact of the web slenderness on the behaviour is minimal, and it is hypothesized that even beams with extremely slender webs can reach almost the full plastic moment due to the very small contribution a thin web makes to the moment capacity.*

1 INTRODUCTION

1.1 Background to local buckling and slenderness limits

Typically, the response of a steel beam under bending can be characterized by a moment – curvature graph, such as the one shown in Figure 1. The initial response is linear, until, the extreme fibres reach the yield stress at the yield moment (M_y), where $M_y = f_y Z$ and Z is the elastic section modulus. At larger curvatures and strains, yielding spreads inwards toward the neutral axis. For the elastic - plastic - strain hardening material, the section yields almost completely and at high values of curvature the plastic moment (M_p), where $M_p = f_y S$ and S is the plastic section modulus.

However, at any stage during this bending process, the beam may fail by either local instability or flexural torsional instability. Figure 2 shows a steel beam that has experienced local buckling, and also separates the individual flange and web plates to illustrate separate buckling modes.

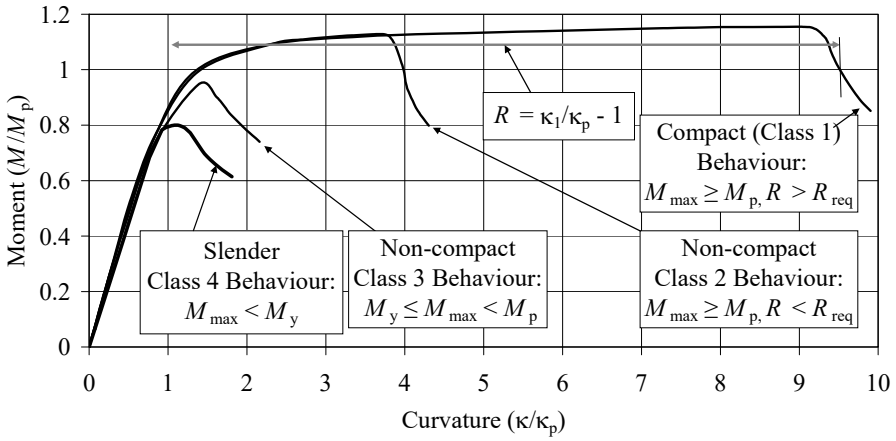


Figure 1: Moment-curvature behaviour of different types of steel sections

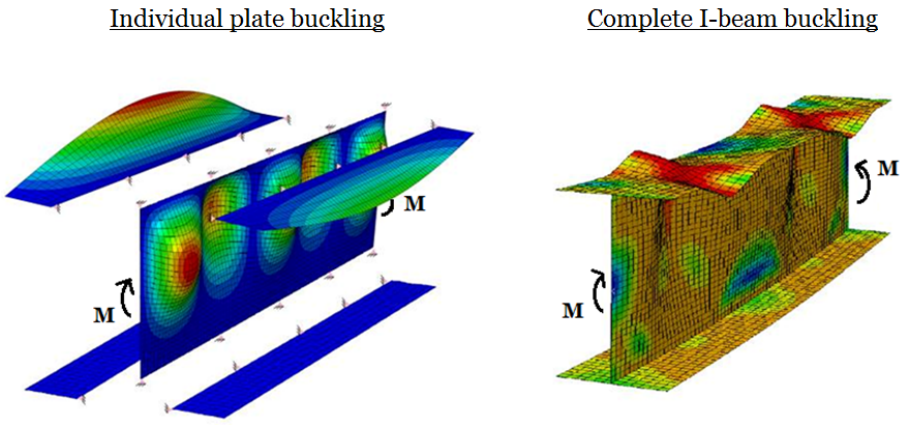


Figure 2: Idealisation of section buckling as plate local buckling of each element

Figure 1 shows also shows how cross-section shapes can be classified as compact, non-compact and slender:

1) *Compact (or Class 1)* sections can attain the plastic moment and have plastic rotation capacity sufficient for plastic design.

2) *Non-compact* sections can sustain somewhere between the yield moment and the plastic moment but have limited rotation capacity. This class is often divided into *Class 2* sections which can reach the plastic moment but with a small rotation capacity, and *Class 3* sections which reach a maximum moment somewhere between the first yield moment and the full plastic moment.

3) *Slender (or Class 4)* sections cannot reach the yield moment due to local buckling.

It is very well established that the elastic local buckling stress (f_{cr}) of plate of width b and thickness t is given by:

$$f_{cr} = \frac{k\pi^2 E}{12(1-\nu^2)(b/t)^2} \tag{1}$$

where k is the plate buckling coefficient. The value of k depends on the nature of the stress distribution across the plate and the support conditions of the plate.

By equating the local buckling stress to the yield stress, one calculates a critical b/t value that differentiates when yielding occurs before buckling (and vice versa). This creates the concept of a slenderness limit between non-compact/slender or Class 3/4 behaviour. Appropriate modifications must be made to account for imperfections and early yield from residual stress. It is likewise possible to obtain slenderness limits between the other classes of behaviour.

1.2 Previous research

When an I-section bends about its stiff axis, the flange is considered as a plate supported on one edge experiencing uniform compression. The web is equivalent to a plate supported on both edges experiencing bending (stress gradient with equal tension and compression stresses on each edge).

A thorough analytical study of local buckling of flanges is Lay [1]. The effects of initial imperfections in the plate (Johnston [2]), and residual stresses (Ueda and Tall [3]) added to the body of knowledge. Tests on twelve I-section beams under moment gradient by Lukey and Adams [4], and eleven tests of Kato [5] were in reasonable agreement with the previous analytical slenderness predictions.

Initial investigations of web local buckling were performed by Lyse and Godfrey [6], and then extended by Haaijer [7], and Haaijer and Thurlimann [8]. Della-Croce [9] and Costley [10] performed tests on continuous I-section beams. Holtz and Kulak [11, 12], Perlynn and Kulak [13], Nash and Kulak [14] conducted experimental investigations, while Dawe and Kulak [15, 16, 17, 18] produced a computer program to analyse local buckling of I-sections to include flange-web interaction, residual stresses, yielding and strain hardening.

The references above represent some of the detailed data that went towards the beam classification slenderness limits in modern steel design standards that have been relatively unchanged since the early 1980s. The approach has been to set independent limits for the flange and the web. However, there have been many studies that have shown that there is interaction between the flange and web when determining section classification.

Kato [19, 20] produced elliptical limits to consider flange - web interaction for various classes of sections. Kuhlmann [21] established a relationship for I-sections between flange slenderness and rotation capacity which included interaction with the web based on a series of 24 tests on I-sections. Beg and Hladnik [22] performed tests on ten I-sections and then used finite element analysis to produce Class 3 limits for I-sections that incorporated interaction between the flange and the web. Kemp [23, 24, 25] produced flange and web slenderness limits that accounted for interaction between lateral buckling, and local buckling of the flanges and webs of I-sections. Stewart and Sivakumaran [26] produced Class 1, 2 and 3 limits for I-section beams that accounted for flange - web interaction. A recent finite element parametric study by Rekha and Kalurkar [27] supports the local buckling interaction between the web and the flange of an I-beam. Furthermore, there have been recent proposals to include interaction considerations into de- sign codes. For example, Shokouhian [28] generated numerical models using non-linear finite element methods aided by ANSYS

software. He proposed that the Chinese steel design code should adopt a generalised slenderness definition to generate new criteria accounting for web-flange interaction on local buckling.

1.3 Aim this paper

Plate web girders often have slender webs and compact flanges to maximise the distribution of area away from the neutral axis. For such shapes, the contribution that the web makes to the overall moment capacity of the beam can be less than 20 %. Even though interaction between flange and web may be present, local buckling in the web of such a section may therefore have minimal impact on the capacity of the beam. The aim of this paper is to use finite element analysis to focus on interaction effects particularly for sections with slender webs.

2 FINITE ELEMENT ANALYSIS OF I-SECTIONS

This paper is significantly based on the undergraduate university theses of Robinson [29] and Kugendran [30]. Full details of methodology and results are available in those references. Finite element analysis was performed in ABAQUS using 4 noded shell elements.

2.1 Geometry and material properties

Typically, the flanges of an I-section represent approximately 60% of the total sectional area, while the remaining 40% area is in the web. As such, the flanges of an I-section contribute to the majority of the I-beam's moment capacity, approximately 80%. Therefore, it is important to investigate realistic web and flange slenderness to minimise large relative size differences in web and flange elements. To avoid unrealistic web and flange combinations, an upper and lower limit was set such that the ratio of web slenderness to flange slenderness was no greater than 20 and no less than 6, ($6 \leq \lambda_w / \lambda_f \leq 20$). Figure 3 plots the realistic data points adopted.

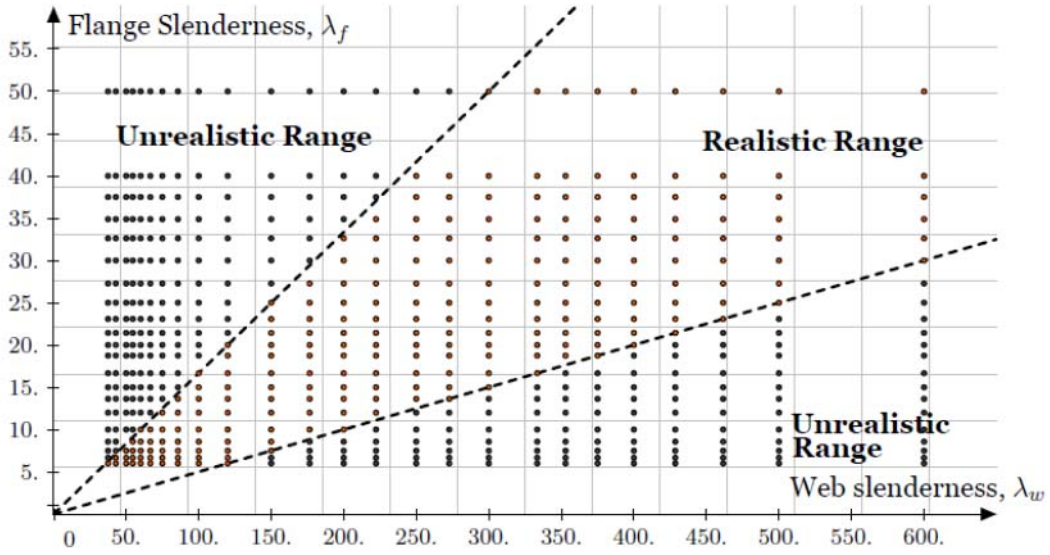


Figure 3: Range of flange and web slenderness in the study

Figure 4 illustrates the dimensions of the model. The dimensions of the I beam were chosen with respect to some of the larger standard Universal Beams (UB) produced by OneSteel Australia (i.e 610UBs). As a general rule of thumb, a length of 3 times the section

depth was assigned to the model as this would be a sufficient length to promote local buckle while simultaneously minimising the effects of flexural torsional buckling. Different flange and web slenderness was achieved by varying the flange and web thickness.

The flange slenderness was defined as $\lambda_f = b/t_f$ (ie it is based on the "flange outstand" or "half flange" width), and the web slenderness defined as $\lambda_w = d/t_w$ using the symbols defined in Figure 4.

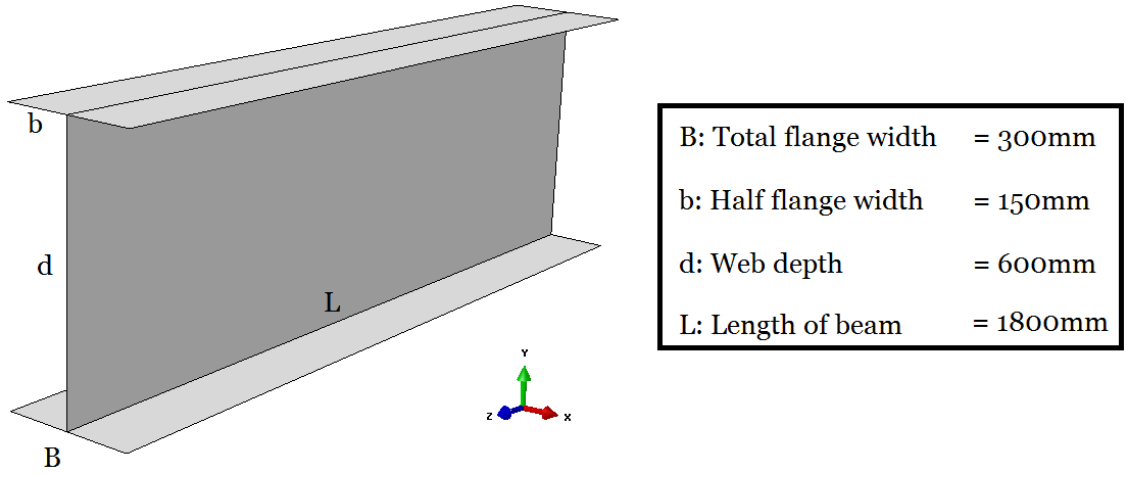


Figure 4: Dimensions of I-beam model

Elastic and plastic material properties of typical steel beams were considered. Figure 5 illustrates the stress-strain response for the 3 various yield stresses. The 3 material properties were chosen with the intent to study the effect of different yield stresses on plate slenderness interaction and classification.

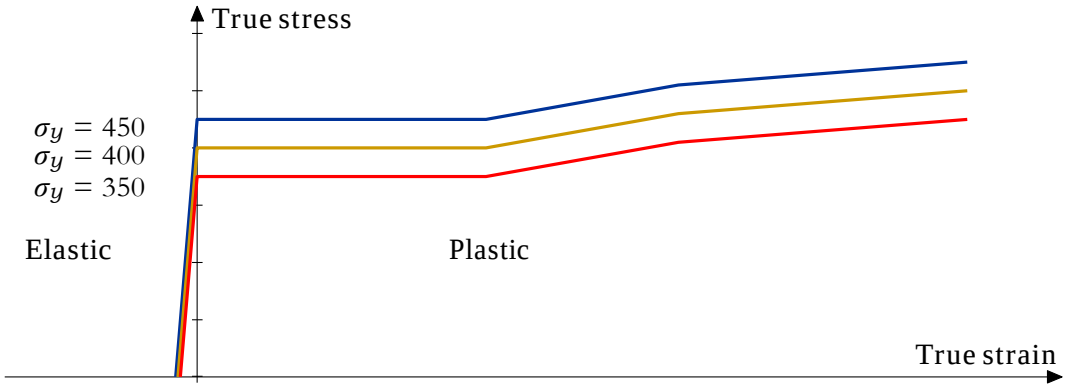


Figure 5: Material properties of steel used

2.2 Loading and Boundary Conditions

The load and boundary conditions (BC) were designed to induce pure bending actions along beam, and to promote pure local buckling. Figure 6 indicate the boundary conditions and loads applied to the model. The boundary condition applied to ends of the beam (RP1, RP2) and at the web-flange intersection along the beam prevents flexural torsional buckling;

by fixing the out-of-plane flexure along the x-direction and the end rotations about the Z-direction.

The loads are applied by inducing an equal and opposite rotation at the centre ends of the beam (RP1, RP2). In order to translate the rotation across the section ends of the beam, a rigid body PIN constraint is used. The rigid bodies were assigned across the entire end sections and linked to their respective end Reference Points (RP1, RP2). By doing this, the motion of the rigid body is constrained by the motion the Reference Points (RP). Consequently, the rotation applied to the reference point governs the entire rigid body. The PIN constrain was used for the rigid bodies as it does not transmit the rotational fixtures (if any) applied on the Reference Points (RP).

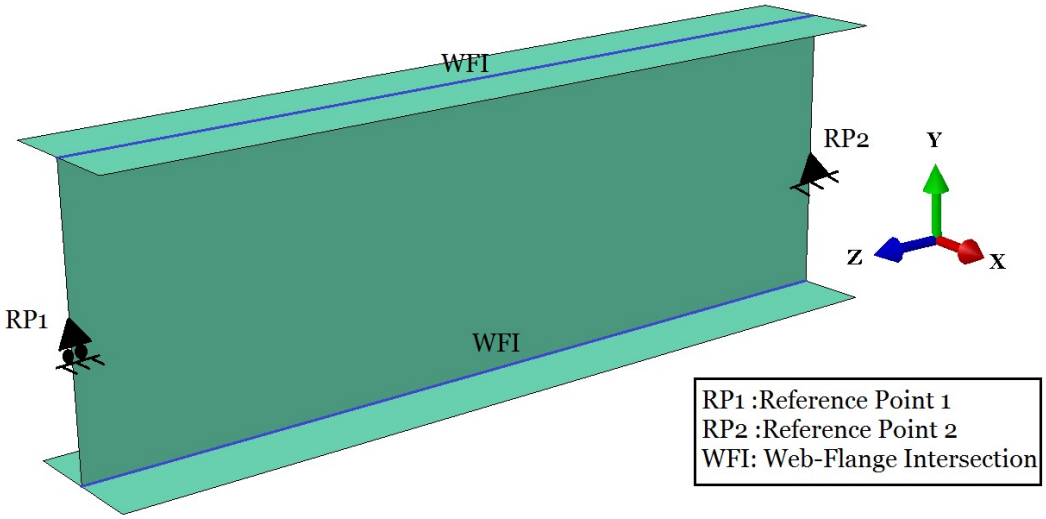


Figure 6: Loading and boundary conditions

2.3 Analysis process and scope limitations

A static, Riks analysis was used for the analysis. Given this was an undergraduate thesis, the scope needed to be limited, and a number of parameters that might normally be included could not be considered. These were imperfections, residual stresses, wider range of flange and web dimensions, and benchmarking against experimental results. Without all these inclusions, the absolute value or positioning of results is not guaranteed, but the trends and general relationships between parameters would be reasonable, and a good starting point for more rigorous analysis later. Mesh refinement was carried out.

3 RESULTS

3.1 Section classification

For each data point of web and flange slenderness combinations, the moment v rotation output was used to classify a section as slender (S), non-compact (NC) or compact (C). Two methods of classifications were adopted, that is, the numerical method and the numerical graphical correction method.

The numerical method was based on the maximum moment achieved by a section. This was then compared with the theoretical yield moment (M_y) limit and the effective plastic moment (M_{pe}) limit. The M_{pe} takes a proportion of the theoretical plastic moment (M_p) that is

considered to be effectively plastic. This accounts for the area towards the middle of the section which experiences minimal strains, and thus is unable to achieve plasticity. The proportion of effective plasticity was determined by observation of the moment v rotation curve of sections that have reached a moment plateau (reached plasticity) slightly below the M_p value. Therefore, a proportion is used to allow the sections with moment plateau curves to reach plasticity while keeping the non-plateau moment curves below plasticity. Subsequently, values of 99.45%, 99.28% and 98.77% were used as the proportion that is effectively plastic for material yield stress (σ_y) of 350, 400 and 450 MPa respectively. Results using this method are shown in Figure 7.

The numerical graphical correction method is an adjustment of the numerical method. Slender sections with moment v rotation graphs that indicates NC behaviours (non-linearity) but with maximum moments just below the yield moment limits were re-classified as NC. Results via this method are given in Figure 8.

The classification plots were fitted with two horizontal boundary lines that separated the C, NC and S regions. Horizontal boundary lines 2 (B2) were placed within the region that consisted of both S and NC sections, and were fitted to impose an equal weighted average number of NC sections above and below the boundary line.

A qualitative judgement, by inspection of the buckled shape, was made as to whether the flange or web appeared to buckle first. This was an inexact methodology, as once one element experience a local buckle, the other element would deform out of cross-sectional flatness due to compatibility. This is compared with a theoretical critical element based on classical elastic critical buckling stress, using an appropriate value of $k = 0.425$ (flange – one edge free) or $k = 23.9$ (web – 2 edges supported with stress gradient),

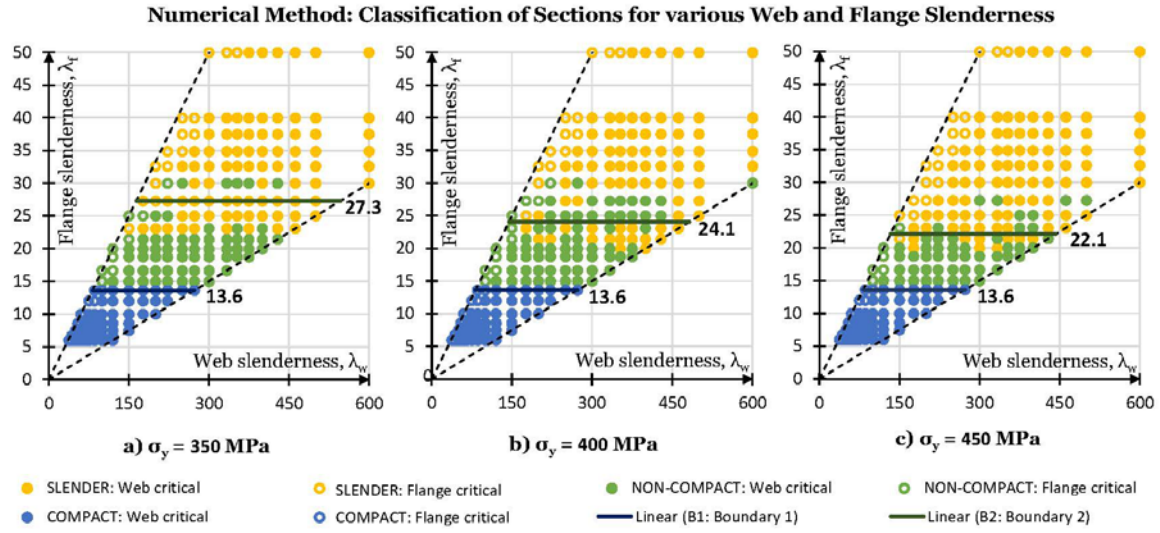


Figure 7: Results – Numerical method

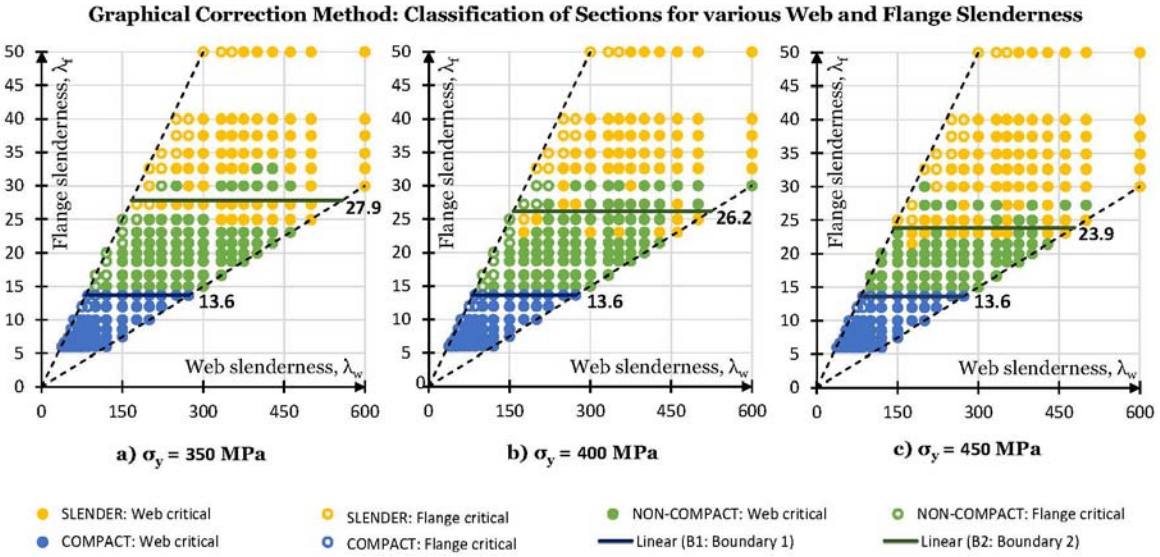


Figure 8: Results – Graphical method

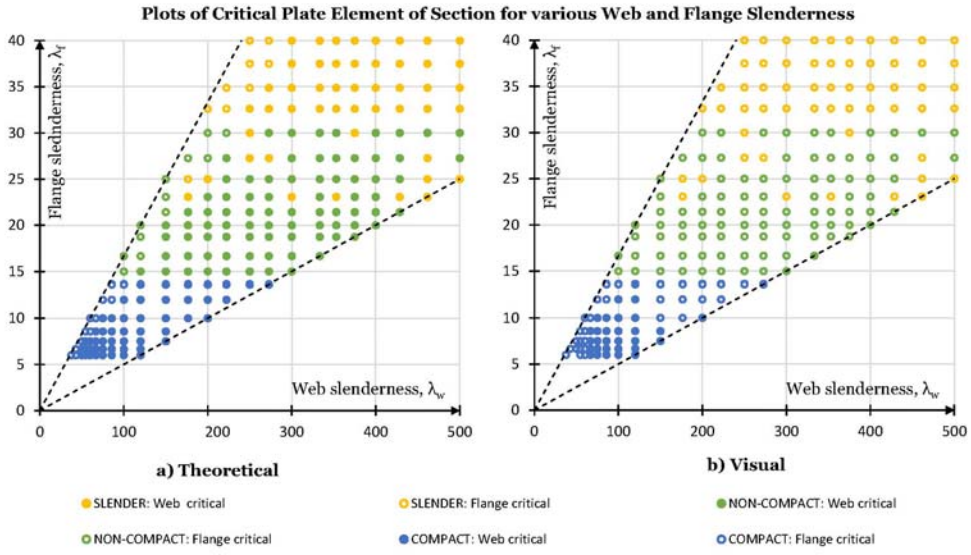


Figure 9: Results – critical element

4 DISCUSSION

4.1 Section classification and slenderness limits

The traditional concept of section classification where flange and web limits are independent is illustrated in Figure 10. Figure 11 shows an idealised representation of limits when interaction between the flange and web is considered.

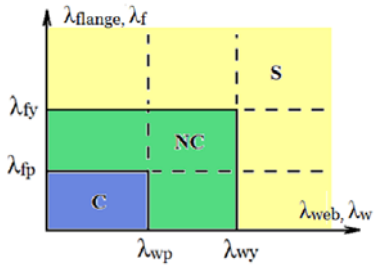


Figure 10: Conceptualised classification with independent flange and web limits

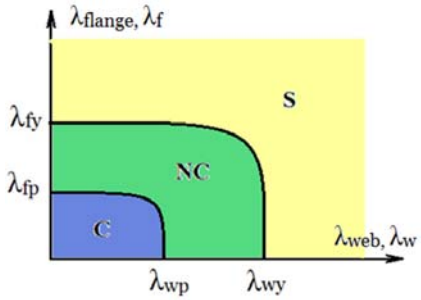


Figure 11: Conceptualised classification incorporating interaction

The classification plots (Figure 7 & 8) were generated to investigate the effects of web and flange interaction on the slenderness limits of I-beams. Both the numerical and graphical correction method yielded similar results with consistent trends and behaviours. The flange yield slenderness limit (B2) indicates a decreasing limit for material properties with increasing yield stress. These values (approximately 13 for plastic limit and 25 for the yield limit) are notably higher than current design rules – but this is to be expected due to the lack of inclusion of residual stresses and imperfections.

The plots show no clear zone (or vertical boundary) between classes, suggesting that the web slenderness is irrelevant and only the flange is important. The inexistence of any web slenderness limit was unexpected, and is thus an indication of the limitations of the adopted method.

This could possibly be explained by looking at the distribution of stresses through the web and flanges of a section. Usually a web local buckle caused by bending is located about two-thirds up the length of a web (assuming compression at the top and tension at the bottom). Hence the ineffective area that is no longer contributing to the moment capacity is both small and close to the neutral axis, and only makes a very small contribution to the moment resistance. If reaching theoretical yield or plastic moment is allowed a small amount of

under-tolerance (say 98%), then a web local buckle is unlikely to prevent the section from reaching its capacity, assuming the flange is still fully effective.

4.1 Critical element

The theoretical critical element was plotted in Figure 9, based on the flange or web that had the lower elastic plate buckling stress, using $k = 0.425$ (flange – one edge free) or $k = 23.9$ (web – 2 edges supported with stress gradient), and compared to the observed buckling element.

Initial observations made from comparing the theoretically and visually (FEA) determined critical element (Fig 9) shows the dominant change from web critical (theory) to flange critical (FEA). The critical stress then depends on the corresponding plate buckling coefficient, k. During the initiation of a web buckle, the flange provides the web with some longitudinal rotational edge restraint which effectively increases the buckling coefficient of the web, k_{web}, thus mathematically increasing the critical stress of the web ($f_{cr,web}$). This leads to a switch in critical element as the critical stress of the web increases to a value greater than critical stress of the flange ($f_{cr,web} > f_{cr,flange}$).

A closer observation of the change in critical element indicates that the change from theoretical web to visual (FEA) flange buckling consistently occurs for webs with greater slenderness. As the web slenderness decreases, the frequency of this change is reduced. In other words, there seems to be greater theoretical agreements of web buckling as the slenderness of the web decreases. Significant convergence of agreement (theoretical and visual FEA) tends to occur for web slenderness of approximately 120 and below. This behaviour is consistent across the various material properties adopted. It was established that the flange provides the web with some longitudinal rotational edge restraint; however the significance of this tends to diminish for webs with lower slenderness. This is likely due to the fact that the relative longitudinal rotational edge restraint provided by the flange to the web reduces for sections with lower web slenderness. As such, the relative longitudinal rotational edge restraint provided to the web is inadequate to cause a sufficient increase in the critical stress of the web, thus not allowing for a change in critical element. The web therefore, remains critical as the critical stress of the flange remains greater than the critical stress of the web ($f_{cr,web} < f_{cr,flange}$).

As the slenderness of the web decreases and consequently becomes stiffer, the degree of relative longitudinal rotational edge restraint provided from the flange to the web decreases. These observations suggest that the theoretical prediction of web buckling is only true for sections with lower web slenderness

10 CONCLUSION

The results generated from the computational experiments for a range of hot rolled I-sections with varying web and flange slenderness, as well as material properties with different yield stress were presented. For sections with high web slenderness, the results successfully provided evidence to support claims for the significance of web-flange interaction. Further, it is clear that the conventional approach of theoretically simplifying the web-flange interaction to a pin boundary condition is unjust for sections with high web slenderness. However, theoretical agreements for sections with low web slenderness justify the theoretical approach of predicting web buckling. Therefore, the usage of plate buckling theory to predict web buckling is only reasonable for more compact sections.

The results also provided reason for the formation of a relation between the degree of web-flange interaction and the geometrical property of an element.

In terms of section classification and slenderness limits, the results failed to bring to light the effects of web-flange interaction. This is likely attributable to the limitations of the adopted method. It is suggested that the exclusion of residual stress is a major contributor to the formation of unlikely results. Thus, this signifies the importance of a parametric study to accurately investigate the classification and slenderness limits of an I-beam.

The results indicated some significant web-flange interaction as well as some limitations in the approach taken. Further study is required to examine the specific impacts of web-flange interaction for a more quantifiable and theoretical refinement of the findings.

An extension of the derived hypothesis will allow for a greater understanding of the degree of rotational restrictions inflicted by the web-flange interaction. This could be done by examining the geometrical properties of the elements in relations to its stiffness. Specific to the findings of this thesis, it is recommended that an investigation be conducted with the aim to form a relative relation between the flange's rotational stiffness with the rigidity of the web. This could lead to findings describing and quantifying the change in critical element for I-beams of various web and flange slenderness combination.

With the intention of rendering the limitations of the adopted method, it is recommended that a parametric study be conducted to allow for a sensible inclusion of residual stress and imperfections. This will allow for realistic simulations of I-beams under pure bending. Therefore, the effect of web-flange interaction on the classification and slenderness limits of I–beams can be assessed with greater certainty. Additionally, the inclusion of the true stress v strain response of steel should be used for material properties of higher yield stress as this allows for greater resemblance of material behaviour.

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