BEHAVIOUR OF UNSTIFFENED WIDE-FLANGE MEMBERS SUBJECTED TO TORSIONAL MOMENT THROUGH ONE FLANGE

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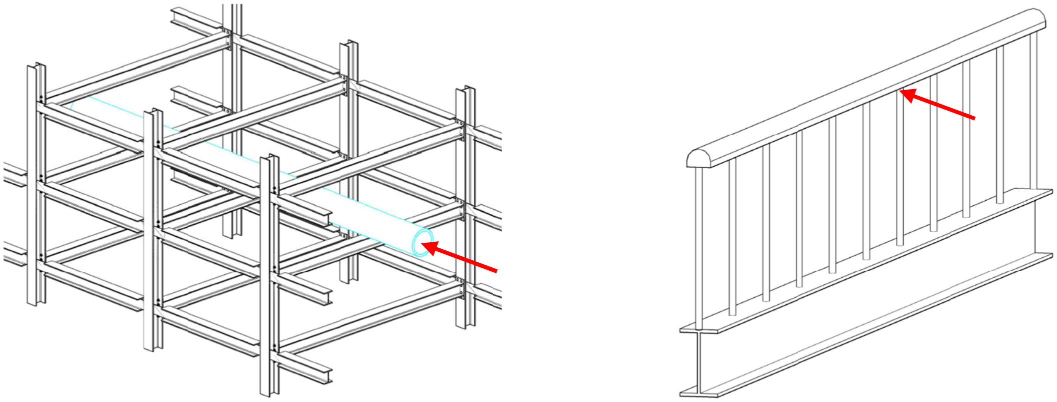
Abstract: It is common for unstiffened wide-flange structural members to be loaded by an adjoining member through the flange. While many load types are readily accommodated by routine design, when the member is loaded torsionally the behaviour is complex and no widely accepted design rules exist. One common example occurs when handrail posts are attached to the top flange of a floor beam, where the horizontal design guard forces induce torsion in the beam. Another is encountered in industrial structures such as pipe racks where a beam that is rigidly connected to a column flange resists weak-axis bending, resulting from hydraulic pipeline forces, that in turn loads the column torsionally. Because of the lack of codified design criteria for cases where the torsional member is unstiffened, it is common to add full-depth stiffeners to transfer the forces to the entire cross-section. However, this adds considerable cost to the joint and is often unnecessary. Unstiffened members subjected to torsional moment through one flange engender phenomena of both single-flange torsion and web bending. Localized bending of the web at the web-to-flange junction and torsion of the flange connected directly to the member delivering the load constitute a complex shared force-resisting mechanism. This paper elaborates on the behaviour of unstiffened members subjected to torsional moment using finite element analysis. Characteristic behaviours of wide-flange members under this type of loading have been explored by conducting a parametric study, varying parameters such as length of member, section depth, flange width and thickness, and web thickness.

1 INTRODUCTION

The need for robustness and economy in the design of structures has led structural engineers to challenges where conventional design methods do not provide the optimal solution, and readily available literature fails to address the relevant issues directly. While wide-flange steel sections are general selected where in-plane flexural loads predominate, in certain instances they are also called upon to resist torsional moments. The torsional moment often results from transverse loading of a member—or several members—adjoining the flange of the wide-flange section, and is usually applied to only one flange of the member. Typically, stiffeners are added to engage the entire cross-section at the point of application of the torsional moment, making it twist uniformly and avoiding local deformations. However, the addition of stiffeners adds considerable cost to the joint, and in some structures this becomes a major cost of construction due to the additional cost of fabrication, labour, and delays, apart from the material cost.

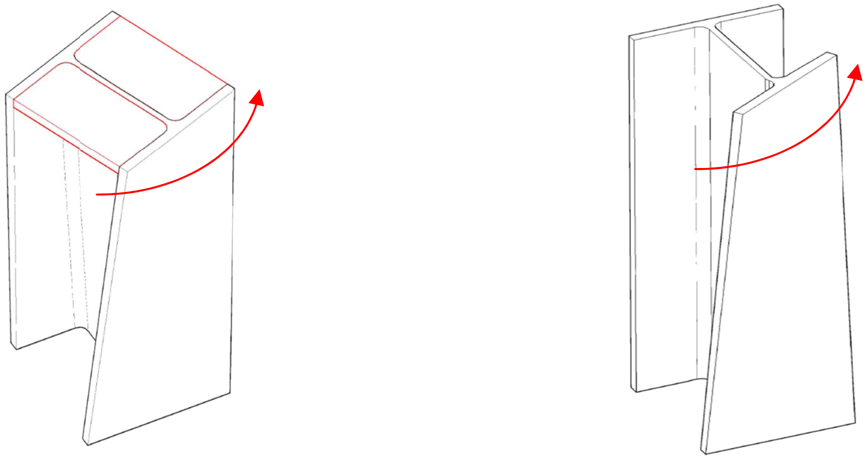
Two examples of relevant instances of where torsional moment can be significant are shown in Figure 1. Figure 1a is a modular pipe rack structure with end-plate moment connections between the beams and supporting columns. Due to hydraulic loading in the pipe, weak-axis moment in the beam is transferred to the column as torsion. Another common case, depicted in Figure 1b, is hand rails where horizontal guard forces induce torsion in the beam top flange. In both cases, the cost of stiffeners can be a critical factor in the design. Another application is in the design of beam bracing where the bracing member is connected to the top flange of the beam to provide torsional restraint, potentially causing local distortion in the beam flange.



a. Modular pipe rack b. Guard rail

Figure 1. Common examples of structures with twisting of flange

Stiffeners welded into place between the member flanges and connected to the web tend to make the cross-section undergo uniform rotation when a torsional moment is applied, but unstiffened members may experience local deformations. This action is resisted in unstiffened members by a combination of flange torsion and bending of the web in the region where the moment is applied. Distorted shapes of a stiffened and an unstiffened wide-flange section under torsional loading through one flange are shown in Figure 2.



a. Torsion with stiffeners b. Torsion without stiffeners

Figure 2. Deformed shape under torsion for stiffened and unstiffened members

Classical elastic torsion theory can be applied to obtain the resisting moment and torsional stiffness offered by the member only if local cross-sectional distortion is prevented by some means such as stiffeners. A W310x129 member loaded torsionally at mid-length through one flange, considering overall member lengths of both 4 m and 8 m, has been modelled with and without stiffeners using the finite element method, and a plot of the applied moment and corresponding rotation is shown in Figure 3. There is a significantly lower moment capacity, as well as stiffness, in cases where no stiffeners are provided (NST), and the difference is larger where the length of the member is shorter. In the case of the 4 m-long member the elastic stiffness is 66% lower than that of its stiffened counterpart (ST), whereas for the 8 m-long member it is 22% lower. The elastic portions of the curves for the stiffened members agree well with classical elastic torsion theory, denoted “Theoretical" in the figure. Moreover, while the onset of inelastic response occurs at a much lower moment in the longer member when stiffened, when unstiffened there is little or no difference.

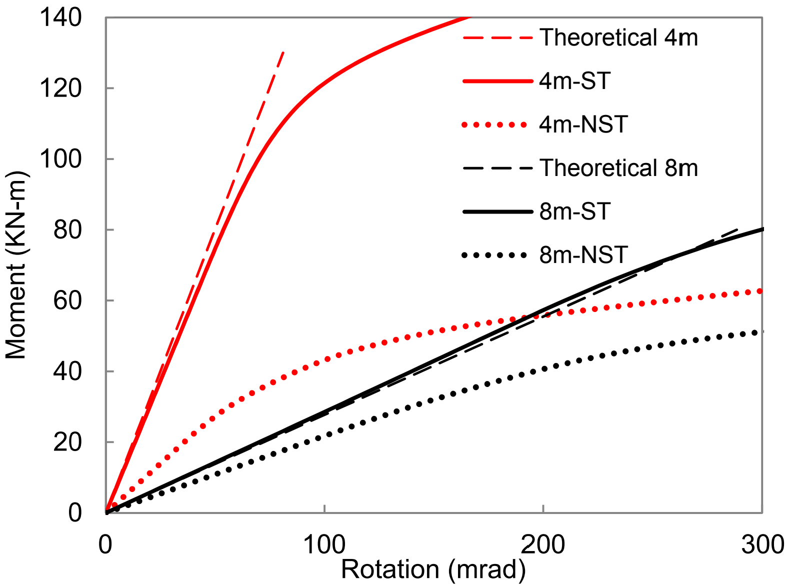


Figure 3. Stiffened vs. unstiffened behaviour under torsional moment

For full utilization of the torsional capacity of the member, stiffeners generally must fully extend between the flanges and be connected to both the flanges and the web. In the case of discontinuous stiffeners between the flanges, local web bending can occur at the root of the stiffener where it terminates. Different scenarios with stiffeners extending half the distance between flanges, three quarters the distance, and full-depth have been compared with the unstiffened case for a 4 m-long W310x129 member loaded torsionally at mid-length. Stress distributions and deformed shapes at an applied moment of 30 kN·m are shown for all models in Figure 4. Figure 5 is a moment–rotation plot for the corresponding models. The cost of installing the stiffeners represented in Models B and C is effectively equivalent, with a premium being imposed for those in Model D due to the fitting of the stiffeners to both flanges. Most importantly, however, the cost represented by Model A without stiffeners would be substantially lower than any of the stiffened options, so the importance of being able to determine accurately the torsional moment capacity of a member without stiffeners is highest when the applied moment is small compared to the full cross-sectional capacity. For the same reason, it is also important that the torsional demands be calculated accurately, rather than being chosen "conservatively" from an overly simplified analysis.

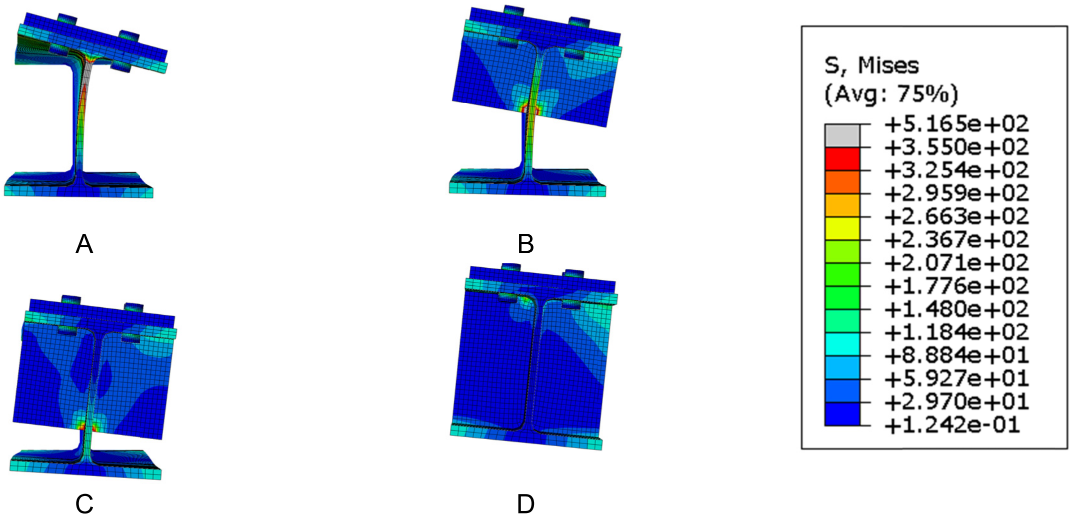


Figure 4. Stresses and deformed shapes of cross-section with various stiffener geometries

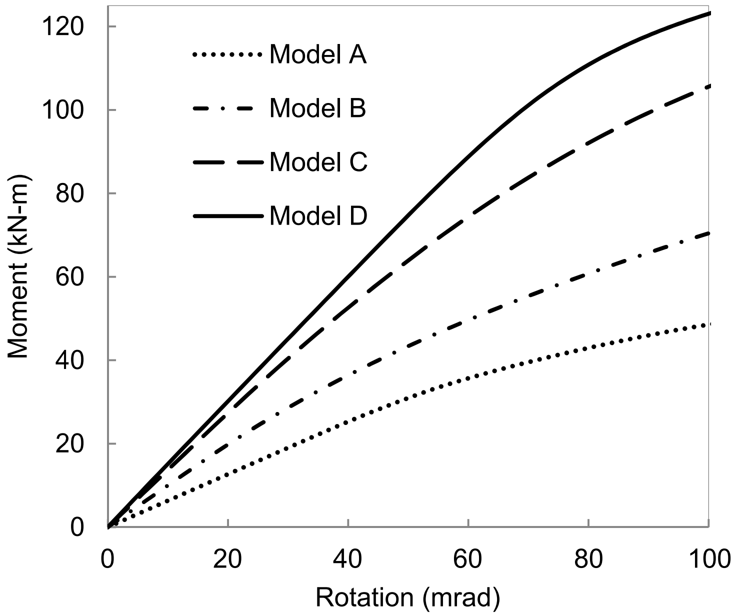


Figure 5. Effect of stiffener geometries on moment–rotation response

2 NUMERICAL MODELLING

2.1 Material Properties

Studies on steel material properties have been performed by Salem and Driver (2010) using finite element analysis, verified by conducting laboratory tests, for the evaluation of appropriate material behaviour to be used for numerical modelling purposes. This research provided the grounds for the material properties chosen for the analyses described herein. These properties are in accordance with CSA Standard G40.21 Grade 350W for the members and ASTM Standard A325 for the bolts.

Metallic elasto-plastic material properties were used for numerical modelling. The elastic part of the typical stress–strain curve was modelled using a Young's modulus of 200 000 MPa, with a Poisson's ratio of 0.3. Strain-hardening values have been incorporated using an isotropic hardening model. Plasticity in the modelling starts after the yield stress of 350 MPa is reached.

2.2 Loading

Full-scale model geometry can be utilized to replicate the manner in which loading is applied on the flange. In Figure 6, a column is connected to a cantilever beam by a moment connection to transfer the moment from the beam to the flange of the column. The various parts of the assembly are shown in the figure. This model takes into account the transfer of force through the bolts in the connection. Using the appropriate properties of the contact between the two steel surfaces, contact is initiated in the first step with the pre-tensioning of the bolts and is maintained as load is applied at the cantilever tip, thus creating weak-axis moment in the beam that is resisted as a torsional moment in the column. Computational effort is large when using this full-assembly model with the detailed connection.

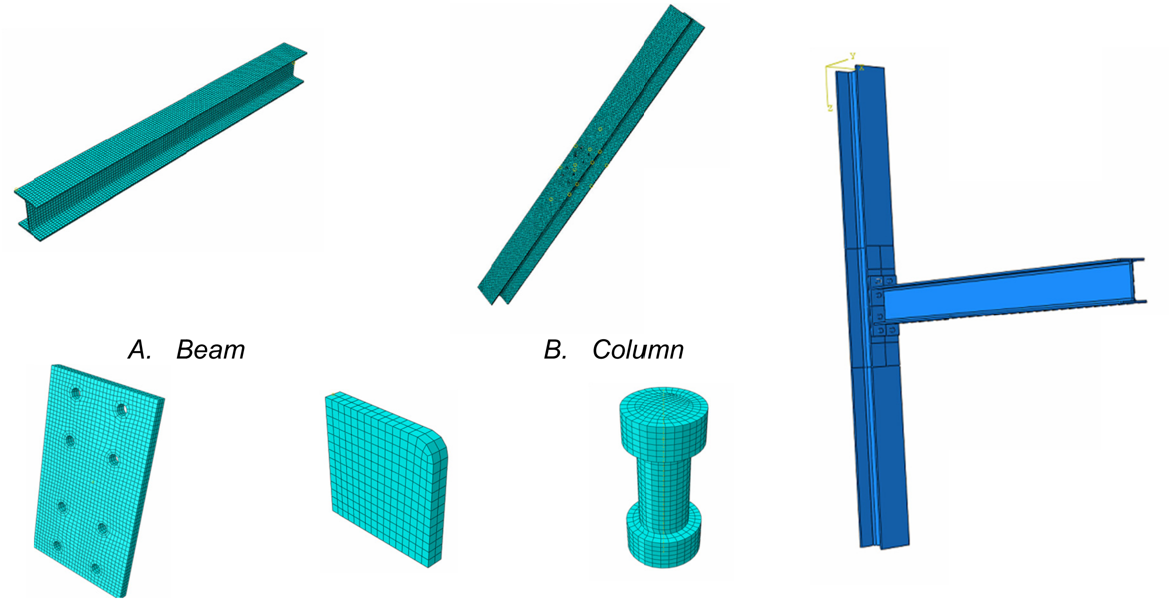

A. Beam
B. Column
C. End Plate
D. Stiffener
E. Bolt

Figure 6. Parts of full joint assembly and corresponding meshes

A simplified model, as shown in Figure 7, can also serve the purpose. Pressure is applied at the bolt locations perpendicular to the flange surface and it remains perpendicular throughout the analysis, thus creating a couple that applies the torsional moment to the flange. The use of pressure is advantageous because concentrated loads on solids using brick elements do not support nodal rotation and therefore as the flange rotates, the force maintains the same direction as applied initially. In addition, much of the localized element distortion that can occur under a point load is avoided by applying pressure on a larger area. This model involves much less computational effort than the full model described previously.

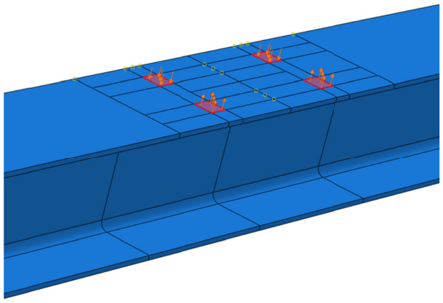


Figure 7. Simplified loading model

Figure 8 depicts the resultant moment-rotation responses obtained by the two different loading schemes for model 4L-300D-300B-8W-12F, which is a wide-flange column section with a length of 4 m, section depth of 300 mm, flange width of 300 mm, web thickness of 8 mm, and flange thickness of 12 mm. There is only a very small difference in the results, particularly within the initial loading stages. For this reason, the simplified loading method is used in the remainder of this section and for the parametric study discussed in Section 3.

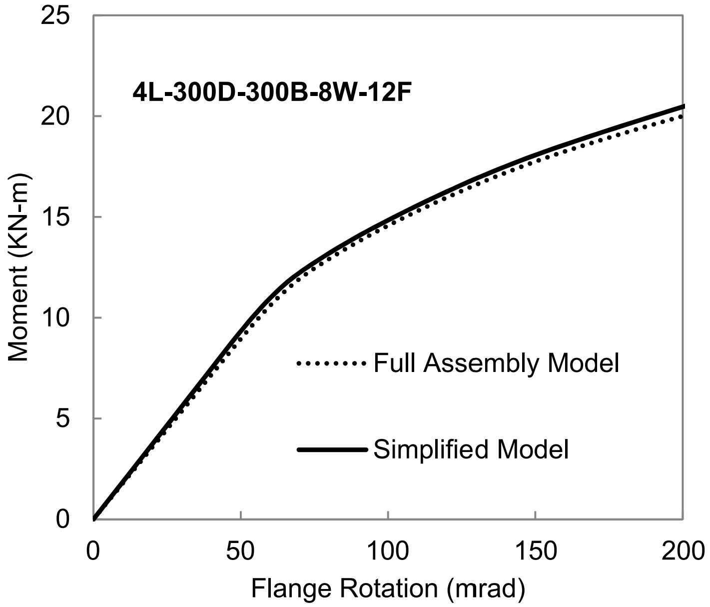


Figure 8. Full-assembly vs. simplified loading model results

2.3 Boundary Conditions

Torsional stiffness is influenced by the boundary conditions at the member ends, even for unstiffened members that tend to deform locally. Figure 9 shows the unstiffened response of a 4 m-long W310x129 member with warping prevented at both ends in comparison to an equivalent case where warping at the ends is unrestrained. Boundary conditions with warping unrestrained were implemented by preventing displacements of all the end nodes in the plane of the cross-section, but releasing the displacements perpendicular to this plane (i.e., along the axis of the member). For the case with warping prevented, nodal displacements in all three directions were fixed. In order to provide comparisons among geometric parameters only, all models in the parametric study have boundary conditions where warping is prevented.

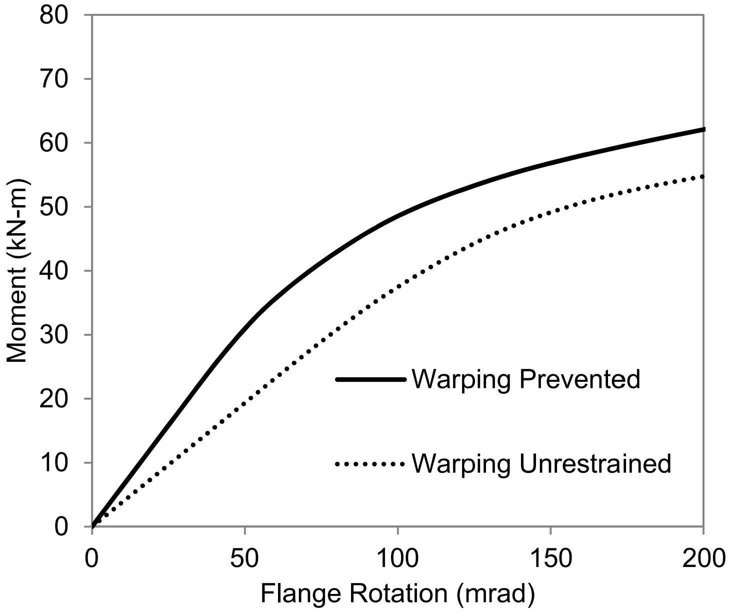


Figure 9. Effect of warping boundary conditions on unstiffened member

2.4 Type of Element And Mesh Refinement

To examine the local web and flange distortional behaviour, solid 3D brick elements were selected. Refinement in the stress variation through the thickness was achieved by increasing the number of elements through the web thickness. Three elements through the thickness with reduced integration resulted in poor transformation of stress from one element to another, whereas with four elements and full integration a gradual change in the stress, without discontinuities, was achieved. Furthermore, reduced integration resulted in less stiffness, as depicted in Figure 10, and inconsistent stiffness comparisons were observed in the parametric study. As a result, for the parametric study results presented in Section 3, full integration was utilized with three elements through the flange thickness and four for the web in the central region of the member.

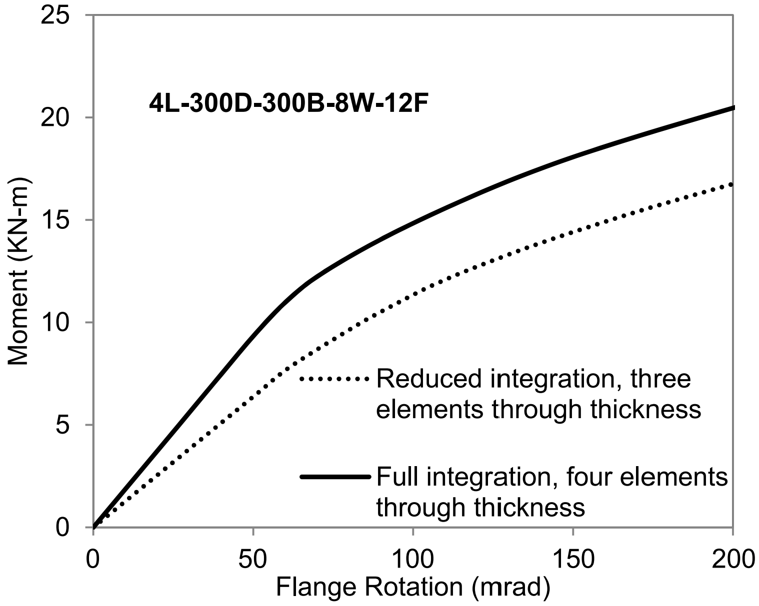


Figure 10. Effect of number of elements through web thickness and integration technique

3 PARAMETRIC STUDY

The torsional resistance mechanism of unstiffened wide-flange members can be devolved into two main components: torsion of the flange and bending of the web. Torsion of the flange can be idealized as a rectangular plate subjected to the torque, for which the significant geometric parameters are the flange width and thickness. For web bending, its thickness is of primary importance. Section depth was also considered in the parametric study as it imparts stiffness variation during bending of the web. Another important parameter is the length of the member, which influences both of the resistance components as well as the overall stiffness of the member. Based on these considerations, five geometric parameters were selected for the parametric study and the combinations examined are shown in Figure 11.

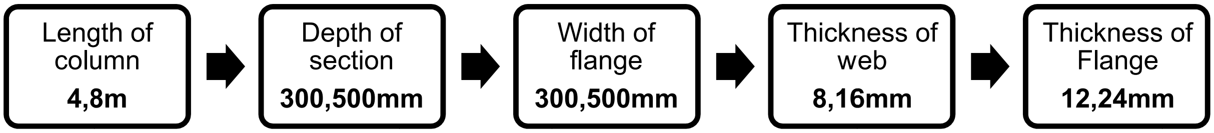


Figure 11. Parameters with combination values

Figure 12 is a typical plot of applied torsional moment and resultant rotation of the flange to facilitate the explanation of general behaviour. Von Mises stress plots at different applied moments are shown for the overall member in the loaded region and for the corresponding web cross-sections in Figure 13 and Figure 14, respectively. Referring to Figure 12, before point “A” the member shows elastic behaviour. Yielding at the surfaces of the web cross-section starts at this point and progress towards the middle surface up to point “B”. A gradual decline in the slope of the curve can be observed after appreciable yielding in this range causes material softening. The entire web thickness becomes plastic at point “B”, whereas the flange remains elastic. Initiation of yielding at the surface of the flange occurs at point “C” and the entire flange thickness becomes plastic at point “D”. It can be observed that both the web (“A” to “B”) and the flange (“C” to “D”) yield gradually by the continuous rotation of the flange. Any inelastic solution must account for the large flange rotation, which approximately doubles from the values shown in Figure 12 if the length is doubled.

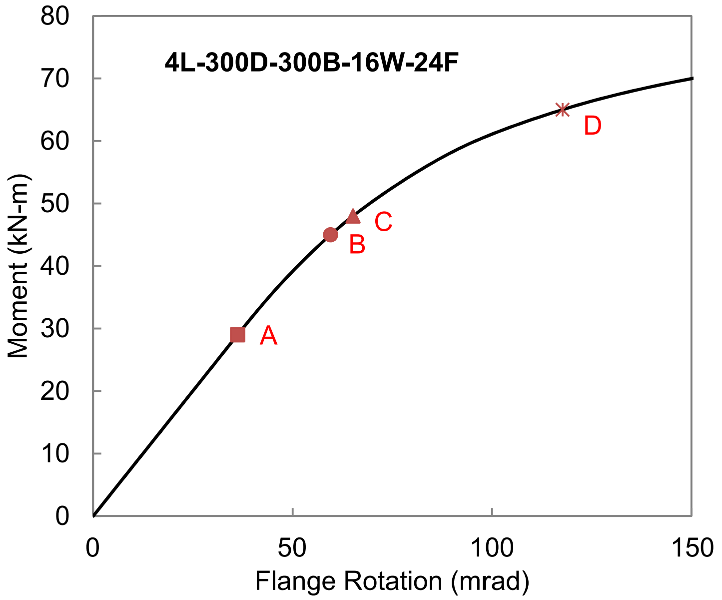


Figure 12. Typical moment-rotation response

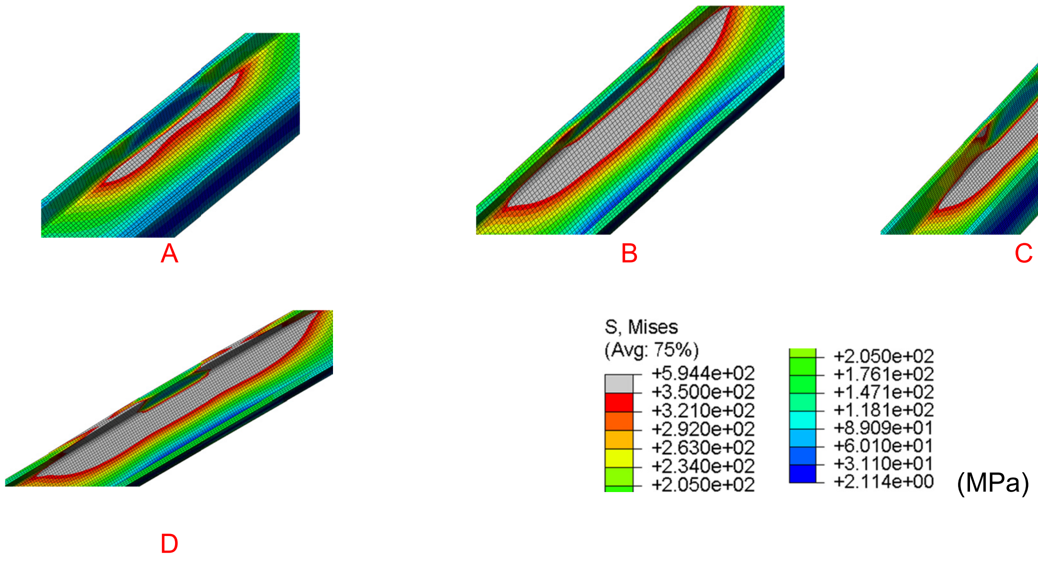


Figure 13. Stress plot at various moments (see Figure 12)

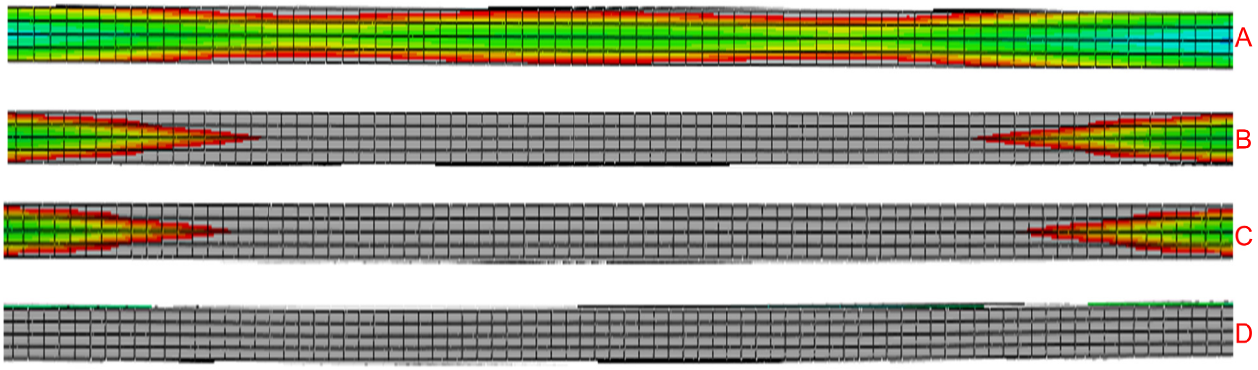


Figure 14. Stress plot for cross-section of web at various moments (see Figure 12)

3.1 Flange Thickness

Increasing the flange thickness from 12 to 24 mm results in a significant increase of resisting moment, but this effect is less conspicuous when the web is thicker, as the flange's relative contribution to the moment resistance decreases. Figure 15 shows selected results by varying the parameters. Comparing models 4L-300D-300B-8W-12F and 4L-300D-300B-8W-24F, not only is there an increase in the moment by thickening flange, there is also an increase in the initial stiffness, as expected.

3.2 Web Thickness

Bending strength and stiffness of the web is decidedly affected by its thickness. The resisting moment and stiffness are both enhanced significantly by increasing this variable. Representative curves in Figure 15 are those for models 4L-300D-300B-8W-12F and 4L-300D-300B-16W-12F.

3.3 Flange Width

Increasing the flange width adds both resisting moment and stiffness. However, as illustrated in Figure 15, by comparing the curves for models 4L-500D-300B-8W-12F and 4L-500D-500B-8W-12F, in comparison to the flange and web thicknesses, the flange width has considerably less influence.

3.4 Depth of Section

As the yielding due to bending of the web initiates at the junction of the web and flange, it was observed that the depth of the section has a comparatively smaller effect than all of the other the parameters investigated in terms of both strength and stiffness. This can be seen by comparing the curves for models 4L-300D-300B-8W-12F and 4L-500D-300B-8W-12F in Figure 15.

3.5 Length of Member

A considerable decline in the initial slope of the moment–rotation curve can be observed by increasing the length from 4 m to 8 m (in Figure 15, models 4L-300D-300B-8W-12F and 8L-300D-300B-8W-12F, respectively).While this decline is expected for stiffened members and can be justified by classical elastic analysis, the localization of the resistance mechanism in the unstiffened case reduces the influence of this parameter somewhat. An important thing to note is that even though the longer length gives rise to a lower stiffness, if the onset of yielding is to be the torsional limit state, approximately the same capacity is achieved for unstiffened webs.

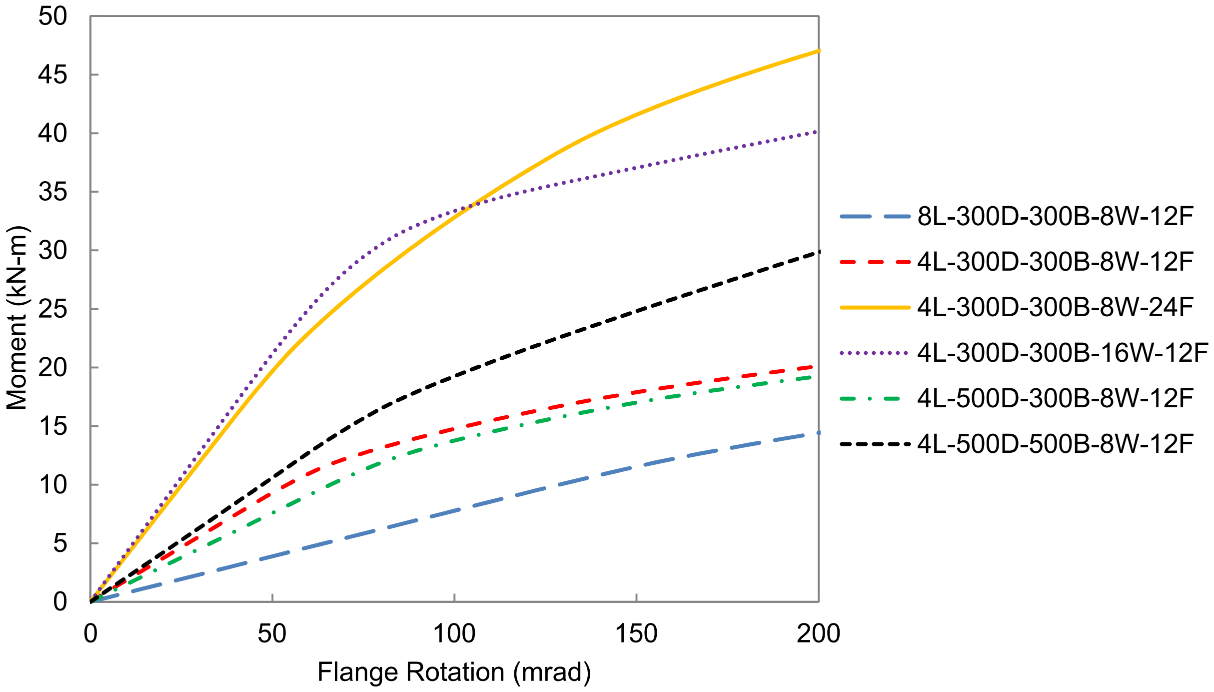


Figure 15. Parameter comparisons

4 CONCLUSION

Wide-flange members without stiffeners when subjected to a torsional moment through one flange undergo local web and flange deformations. Both the moment-carrying capacity and stiffness tend to be lower than when the moment is distributed to the entire cross-section with the aid of stiffeners. However, for applications where the full torsional cross-sectional capacity is not required, an understanding of the unstiffened behaviour is essential for investigating the potential elimination of stiffeners, which add considerable cost to the joint. To study the unstiffened member behaviour, a comprehensive parametric study is in progress and preliminary results are presented herein. Parameters found most important to the resistive moment are the flange thickness, web thickness, and flange width, whereas the depth of the section and the member length have minimal effect within the range of parameters considered. Results from this parametric study will be used to develop a test matrix to provide full-scale experimental evidence and further data for evaluating the strength and stiffness of unstiffened members subjected to torsional moment through one flange, and ultimately a design methodology will be proposed.

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