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PREDICTING THE CAPACITY OF ALUMINUM COMPRESSION MEMBERS WITH COMPLEX CROSS SECTIONS

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Abstract: The purpose of this paper is to present the results for buckling tests for aluminum compression members with two cross section geometries and three lengths, and compare the results with predictions based on several design codes and results from 3D nonlinear finite element analyses (FEA). The cross section geometries consist of a rectangular hollow structural section (HSS) member, with a single slot running the length of the member at two different locations, resulting in different local buckling capacities for the different plate elements in the cross section. The tested geometry was designed to represent the more complex extrusion shapes that are possible and commonly seen in aluminum structures. The results show varying degrees of conservatism in the investigated design codes. The FEA procedure employed general does a good job of predicting the test results. The accuracy of this procedure could likely be further improved with more careful measurement of the material strength, initial imperfection geometry, and boundary conditions. Other recommended areas for future work include looking at a broader range of compression member lengths, cross section geometries, and aluminum alloys.

1 INTRODUCTION

A study of design provisions for compression members in several design standards for aluminum structures revealed significant differences for certain slenderness ratios and cross section geometries. Cross section geometries consisting of open sections with individual elements having vastly different local buckling stresses were identified as the ones that resulted in the most significant variations in the design capacities according to these standards. In order to investigate the matter further, a small experiment was designed, which involved performing buckling tests for aluminum compression members with two cross section geometries and three lengths, and compare the results with predictions based on the various design codes, as well as with results from a subsequent 3D nonlinear finite element analysis study. The tested cross section geometries were chosen to represent the more complex extrusion shapes commonly seen in aluminum structures. In the following sections of this paper, the various design codes are discussed and the completed investigation is described. Based on the results of this research, recommendations are made concerning aluminum compression member design and future research needs.

2 EVALUATED DESIGN CODES AND METHODS

2.1 CSA S157 / S6

The CSA S157 design standard assumes that as soon any element of a cross-section has buckled, the entire column has failed, with some provisions for post-buckling strength. The method employed in this standard is based on the work of Marsh (1998) on design methods for stiffened plate elements.

In order to implement the method, elements of a cross-section are first analyzed individually to determine which element has the lowest local buckling stress, if any. In the case of elements supported on both edges (e.g. webs), an increase in capacity is allowed due to post-buckling capacity. The flexural and torsional buckling loads are then calculated, using buckling reduction factors multiplied by a limiting stress, F_o. If there are no welds or local buckling, then F_o is taken as the yield stress F_y. To account for the effects of local buckling, F_o is taken as the smallest local buckling stress of any of the elements.

This method of considering local buckling is naturally conservative. Essentially, it can be thought of as a lower bound solution for the capacity of a column, since the strength is governed by the weakest element of a cross-section, regardless of reserve strength after the first element buckles.

2.2 Aluminum Design Manual

The Aluminum Design Manual (ADM) is the principal aluminum design standard in the United States. For compression members subject to local buckling, two methods are allowed: the weighted average method (WA) and the direct strength method (DSM), as discussed in the following paragraphs.

2.2.1 Weighted Average Method (WA)

According to the weighted average method every element of a cross-section is allowed to reach its limiting stress, whether it be buckling or yielding, and the strength of the section is taken as the sum of all strengths of elements. This can be thought of as an upper-bound solution, since it assumes every part reaches its full capacity – in theory, there should be no reserve strength at all. This theory is based on the works of Crockett (1940), on the use of slender elements in aerospace applications.

To account for a partial loss of stiffness associated with local buckling, an upper limit is provided on the capacity of the column. This limit is based on the element with the smallest elastic local buckling stress, since the loss of stiffness would begin at that point. It does not account for post-buckling capacity. The provided formula was calibrated for I-sections and hollow tubes but is conservative in other cases.

2.2.2 Direct Strength Method (DSM)

The direct strength method is an alternative design method, which allows any analysis to be used to find the elastic buckling stress of the cross-section. This method lends itself well to using computer techniques such as finite element analysis (FEA) or the finite strip (FS) method, often used in the design of cold-formed steel. The DSM has the advantage of allowing software analysis to consider more complicated cases, such as oddly-shaped elements or interactions between modes and elements.

When implementing the DSM, the same interaction as the WA method is used to consider the combination of local and global buckling modes. However, since the elastic buckling stress for the entire cross section is calculated, as opposed to the weakest element, this generally provides less conservative results, particularly with cross-sections for which the original equation was not calibrated.

2.3 Eurocode 9

Eurocode 9 makes use of the effective thickness method, which is similar to the weighted average method in many practical situations. The thickness of slender elements is reduced proportionally to their buckling stress, which reduces the effective area and thus effectively increases stress on the section.

The code also considers the effects of distortional buckling for stiffened elements, by requiring all local buckling modes, including those with the element and its stiffener behaving as one element, to be inspected. The current code allows the use of gross sectional properties to calculate global buckling modes, for which the capacities are then scaled by the effective area. This provides a significant relief in complex cross-sections where properties may require intensive calculations or inaccurate approximations.

2.4 CSA S136

CSA S136 is the main standard for cold formed steel in North America, and the most comprehensive for local buckling calculations. It includes a direct strength method, which is very similar to the DSM method in the ADM, however it also considers the effects of distortional buckling distinctly from local buckling. This affects some members of medium length, where the distortional buckling stress may be lower than the local buckling stress. Since CSA S136 uses inelastic buckling curves based on the behaviour of steel members, the calculations may not be assumed to represent the true behaviour of aluminum columns, but are used herein (with appropriate modifications) as an additional comparison point with the other codes.

3 EXAMINED CROSS-SECTIONS

Two cross-sections were used to compare the five analysis methods, both based on a 150 x 50 x 3 mm rectangular tube, with a slot on a side (Figures 1) and on the bottom (Figure 2). Table 1 provides dimensions for both cross-sections. Additional to the code calculations, a finite element model was used to estimate capacities, as well as laboratory tests of both sections at three lengths: 300, 900, and 1800 mm.

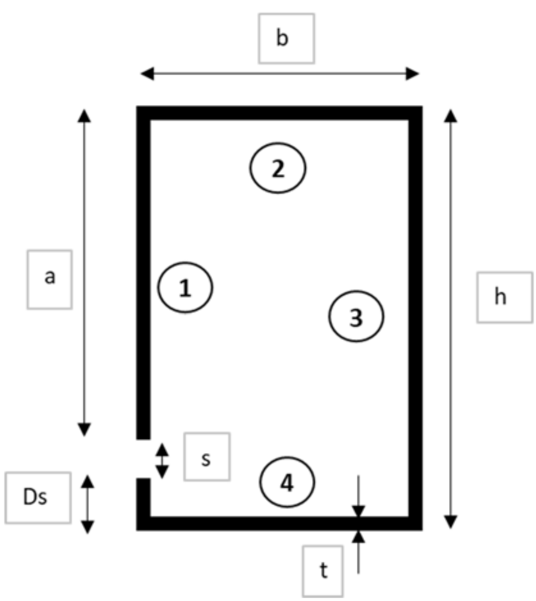

Figure 1: Side slot cross-section.

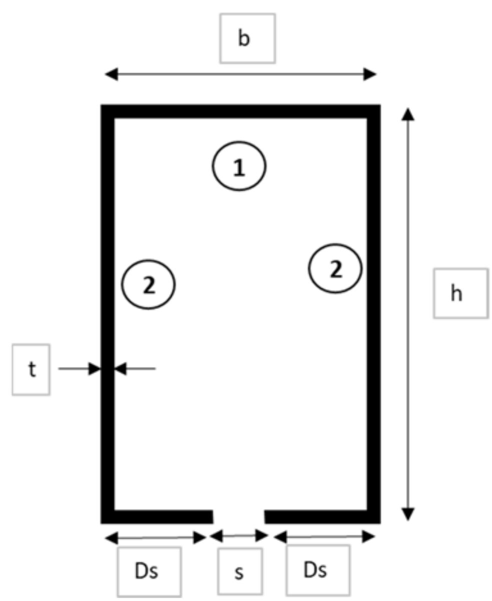

Figure 2: Bottom slot cross-section.

Table 1: Dimensions of cross-sections.

	Side Slot (mm)	Bottom Slot (mm)
b	51	51
h	152	152
D_s	10	24
s	3	3
a	139	N/A

The samples were composed of extruded 6061 aluminum of an unknown temper. One tension test and hardness tests were used to determine the yield strength, which was found to be approximately 165 MPa The modulus of elasticity was taken as 70 000 MPa, as is commonly assumed for aluminum.

3.1 Laboratory Testing

Laboratory tests were conducted on the 300, 900, and 1800 mm long specimens to observe their behaviour. Two aluminum base plates were used at the ends to allow the columns to seat evenly and minimize induced eccentricities from non-perfect end conditions. Strain gauges were installed to observe the load in elements of the cross-section, detecting local buckling and P-δ effects before global buckling.

3.1.1 Side slot tests

During the side slot tests, Element 1 (see Figure 3(a)) was observed to buckle very early, with noticeable deflection at an average stress of approximately 30 MPa. There was significant post-buckling strength, with the ultimate average stresses more than triple that value. The 300 and 900 mm samples failed by a combination of yielding and local buckling, while the 1800 mm sample failed by flexural buckling after the onset of local buckling (Figure 3(b)). The ultimate average stresses were 126, 120, and 109 MPa.

3.1.2 Bottom slot tests

The bottom slot sample behaviour was closer to the prediction by the analyses and codes. The 300 mm sample failed by local buckling of Element 2, with no post-buckling strength. The 900 mm sample did not fail in a distinct mode: a combination of local, distortional, and flexural-torsional buckling was observed (Figure 3(c)). The 1800 mm sample failed in pure flexural-torsional buckling (Figure 3(d)). The ultimate average stresses were (in order of increasing length) 122, 92, and 55 MPa.

3.2 Finite Element Analysis (FEA)

The specimens were modelled in the ABAQUS finite element software to estimate the true behaviour of the cross-sections at longer lengths than the tests. The Riks analysis method was used to observe the post-buckling behaviour. The ends were modelled as fixed to reflect the loading conditions of the testing. Quadratic elements were used. A sensitivity study on the peak load was performed on the model to confirm convergence. An initial imperfection was introduced to the model, its shape was taken as a linear combination of the first local buckling mode and the first global buckling mode. For local buckling, the initial imperfection had a magnitude of *B*/500, where *B* is the local characteristic dimension of the element, and for global buckling, a magnitude of *L*/500 was used, with *L* equal to the specimen length.

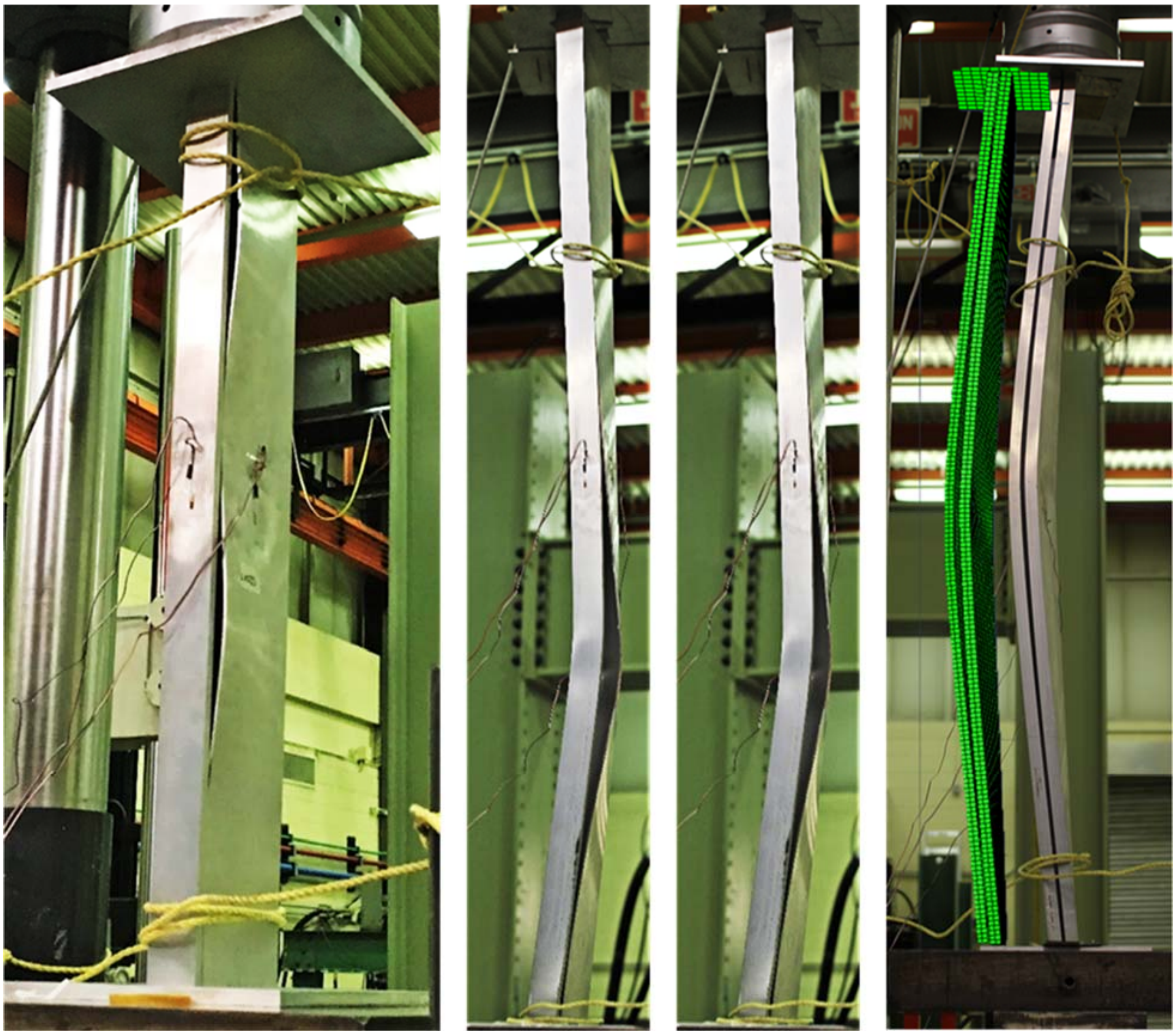

Figure 3: Test photos: (a) buckled Element 1, at 30% of ultimate load on 900 mm sample, (b) buckled 1800 mm sample (c) buckled 900 mm sample, and (d) buckled 1800 mm sample (with FEA model).

4 COMPARISON

4.1 Local Buckling Capacity

The capacities obtained for the 300 mm samples were deemed to best represent the local buckling behaviour. Figure 4 compares the calculated capacities to the laboratory and FEA results.

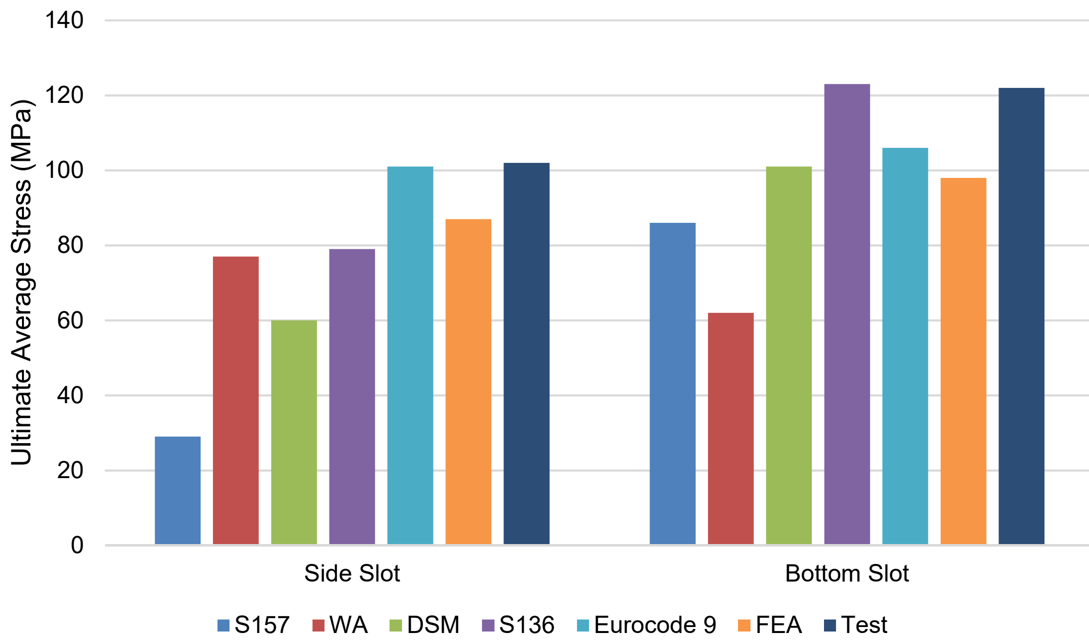

Figure 4: Local buckling ultimate stresses.

In all cases but for Eurocode 9, the codes significantly underestimate the local buckling capacity of the side slot sample. The S157 code predicts a strength of less than one third of what was observed, which is explainable by the fact that it does not consider any post-buckling strength. The ADM WA and Eurocode methods both allow post-buckling strength, with the Eurocode predicting almost exactly the local buckling capacity. The ADM WA method is the only method that predicts a lower value for the bottom slot – this is a result of its calculation method for lip-stiffened elements.

The two approaches based on the finite strip method differ significantly – this is because S136 considers distortional buckling, which occurs at medium lengths, distinctly from local buckling. The distortional buckling stress being lower than the local buckling stress, the ADM DSM has a plateau, which is lower than the local buckling stress used in CSA S136.

4.2 Column Curves

Column curves were generated to examine how the different codes predict the capacity. The test and FEA results were also plotted for comparison purposes.

4.2.1 Side slot

Figure 5 shows the column curves for the side slot cross-section. As can be seen, the codes vary significantly in their predictions of local buckling and their inelastic portion, and then converge for the global buckling mode. The Eurocode 9 curve matches closely with the test results in the local buckling range, but then joins the other curves and becomes very conservative for the longer member lengths. The ADM WA method has a high plateau at short lengths, but sharply decreases due to the interaction equation with global buckling, which does not account for post-buckling strength.

The FEA results proved to be slightly on the conservative side. This is likely due to the use of the code-suggested $L/500$ amplitude of the initial imperfection. In reality, such a large imperfection would be improbable, and the capacity would be higher than predicted with the $L/500$ amplitude.

At longer lengths, the codes all predict strengths much smaller than predicted by FEA. Since all the codes have interaction equations between local and global buckling stresses, it is likely that the extremely low first-buckle stress reduces the capacity of the cross-section. Other factors such as the limited material strength data and end support idealization have likely also affected these results.

Overall, the side slot cross-section proves rather difficult to analyze: different codes vary by up to 300%, and the predictions are generally very conservative. This is due to the vastly different local buckling strengths of the different elements in the cross section for this configuration.

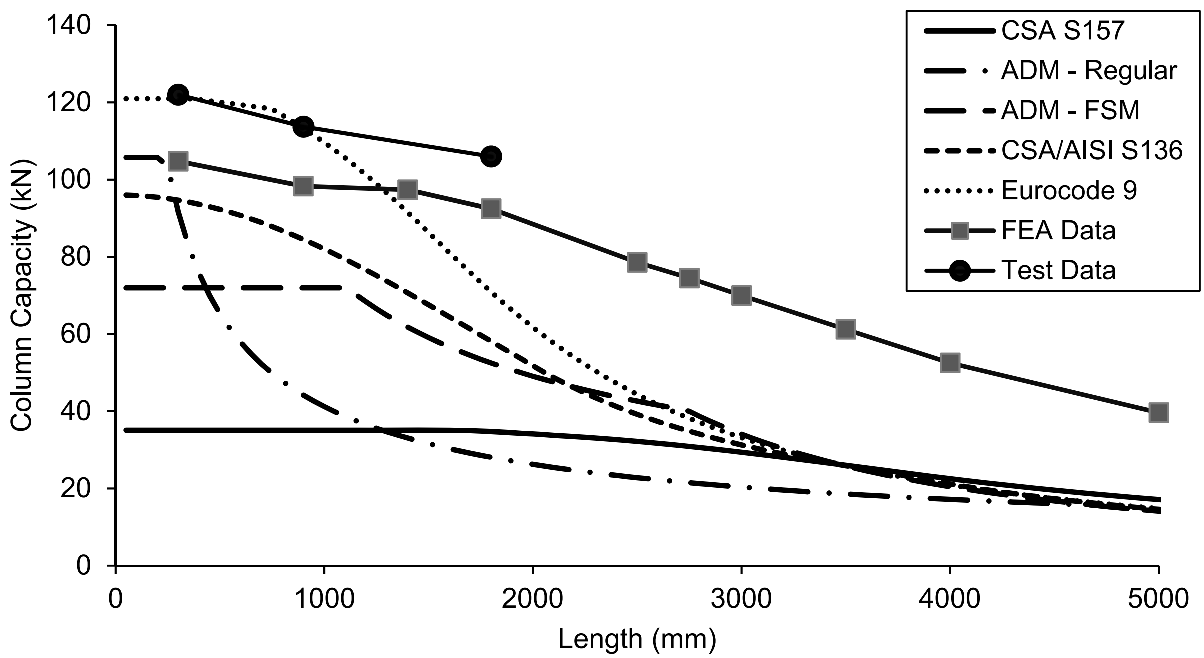

Figure 5: Column curves for the side slot cross-section

4.2.2 Bottom slot

In the case of the bottom slot, the codes predict much more similar values. Figure 6 displays the column curves calculated. The CSA S136 code predicts very close values to the test strength. This could be because it considers distortional buckling distinctly, to which this cross-section is subject. The use of the steel-based inelastic buckling curves also alters the results somewhat. The ADM WA method predicts lower capacities, because the ADM inelastic buckling curves are more conservative in this situation.

Overall, this cross-section, which is symmetrical and does not have any extremely slender elements, is much more well-behaved. The codes predict capacities within +/- 30%.

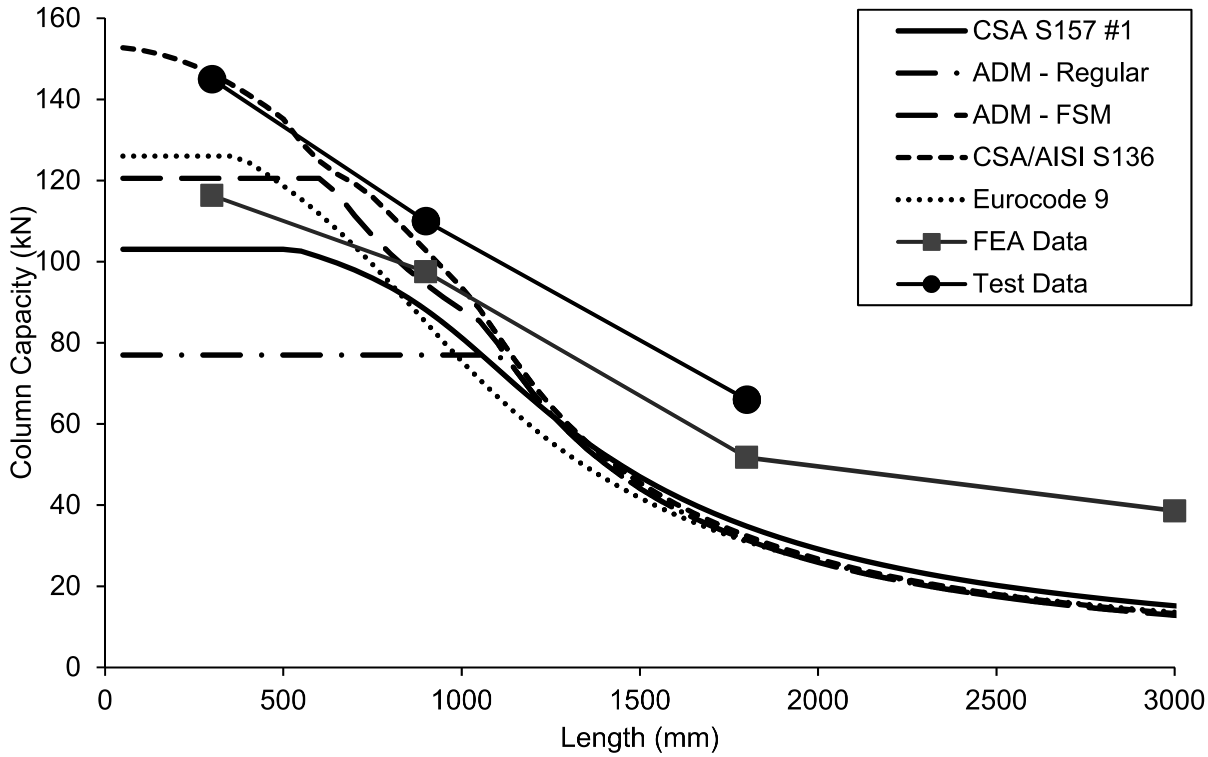

Figure 6: Column curves for the bottom slot cross-section

5 CONCLUSIONS

Based on the research results presented in the previous sections, the following conclusions are drawn:

- The results show varying degrees of conservatism in the investigated design codes.
- The FEA procedure employed general does a good job of predicting the test results.
- Complex cross-sections can have post-buckling strength, which should be taken advantage of, since it might be very significant for certain geometries, such as in the side-slot configuration.
- Cross-sections may be affected by distortional buckling. For short members, this buckling mode should be treated separately from local buckling as in CSA S136, since it usually occurs in medium-length members and longer. The bottom slot configuration is an example of this, where the ADM DSM method gives lower results than CSA S136 even though the same FS analysis was used.

The accuracy of the employed FEA procedure could likely be further improved with more careful measurement of the material strength, initial imperfection geometry, and boundary conditions. Other recommended areas for future work include looking at a broader range of compression member lengths, cross section geometries, and aluminum alloys, in order to enable further validation and generalization of the trends reported herein to a broader range of compression member configurations.

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