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Stub column response in light of local vs distortional buckling

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Abstract
The objective of this paper is to study the effect of distortional buckling on typical stub column testing used by industry to determine the effective area of cold-formed steel members under compression. Testing standards such as AISI S902 are intended to determine the effective area of stub columns experimentally; however, other failure modes such as distortional buckling or premature failure at the ends of the specimens can potentially occur prior to cross-section local buckling, and therefore the effective area could be underestimated. This can result in underestimating the capacity of longer compressive members in the design of real structures, where the overall capacity of the cross-section could be knocked down due to local-global buckling interaction. An experimental study on lipped channels and rack sections with relatively low distortional buckling capacity, compared to local buckling capacity, has been conducted at the Thin-Walled Structures Laboratory in Johns Hopkins University to shed light on the effect of other failure modes on the calculation of the effective area. Different end conditions including bare, in-track, welded, clamped, and also different means of artificially postponing the distortional buckling are examined experimentally, and practical recommendations have been provided on how to conduct experiments to get a more realistic effective area in stub column testing.

1. Introduction
The axial capacity of cold-formed steel compression members can be determined by the effective width method (EWM) or the direct strength method (DSM) as detailed in design specifications such as AISI-S100-16. There are some limitations on the applications of these design methods, when the cross-sectional shape is very complicated, or when unique hole patterns exist in the member. Even for DSM, which has provided a means to predict the capacity of members with almost arbitrary cross-sectional shape and holes, there are still benefits to testing columns and determining the axial compression capacity. This is especially true when a large number of the same cross-sections are commonly being used, and having the full benefit of the tested capacity can provide important efficiency in design. One of the best examples of this situation is the rack industry. Rack sections are typically perforated and have unique repeating hole patterns. Rack

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cross-sectional shapes can also be more complicated than a typical cold-formed C-channel shape. Accordingly, it is common for rack designers to rely on test results to handle the hole patterns and unconventional cross-sectional shapes. AISI 902-17 is a test standard to determine the effective area of columns via a stub column test. It is assumed that the stub columns will fail in local buckling and not other global failure modes due to the short length of the stub columns. The standard is mainly based on studies conducted in the 1980's with little subsequent updating.

While distortional buckling of cold-formed steel members was observed in past physical experiments, only relatively recently, since 2007, has this mode been adopted as an independent failure model in design specifications such as AISI-S100. Distortional buckling is a form of instability in the cross-section in which a group of elements buckle together and results in rotational and potentially lateral deformation of a sub-set of elements. In the case of lipped C-channels, in distortional buckling, the flanges and lips buckle inward or outward and turn around the flange-to-web juncture. This mode of failure can potentially happen prior to or after local buckling of the member and, in some cases, may interact with the more common local buckling and global buckling.

The main question addressed by this study is: How can we make sure the effective area determined by using stub column testing is not including a reduction from distortional buckling? Answering this question in the past was perhaps easier as distortional buckling was not addressed in the design specifications, but now, we know there is a possibility that a "stub column" may fail in distortional buckling rather than local buckling. Accordingly, it is expected that one should consider distortional buckling more explicitly in the design and test protocols. This paper has an analytical and experimental approach to examine the current stub testing standard as in AISI-S902-17, and to provide recommendations on incorporating special care with regard to the distortional buckling mode of failure in stub column testing.

2. Identifying potential for distortional buckling in stub columns

AISI-902-17 provides specific recommendations for stub column testing to avoid global buckling and is intended to ensure that the failure mode is local buckling. For a plain C-channel cross-section with no hole pattern, these recommendations come to simple requirements on the length of stub column, where the length should be shorter than $20r_y$ but longer than $3D_{web}$, where r_y is the minimum radius of gyration of the section, and D_{web} is the depth of the cross-section. The first requirement is to prevent global buckling, and the latter one is intended to make sure the specimen is long enough to minimize end effects. It is hypothesized is that the suggested length may not necessarily prevent distortional buckling from happening prior to local buckling. If this happens, the test results will not provide the local buckling capacity of the stub column, but rather include some form of distortional buckling as well.

Figure 1 provides the ratio of the nominal axial distortional buckling capacity, P_{nd}, and local buckling capacity, P_{nl}, of stub columns from lipped channels across several cross-sections in the SFIA (SFIA 2015) catalog. These capacities have been calculated by DSM in AISI-S100-16. As shown, for the selected cross-sections, the P_{nd}/P_{nl} ratios are less than one, which means that if unrestrained AISI-S100-16 predicts that distortional buckling would fail at a lower load than local buckling. For a short stub column, where distortional buckling is partially restrained by length and end conditions, it is still possible that distortional buckling could happen prior to local buckling in a stub column test of these cross-sections. Since distortional buckling is checked separately in design, the effect of distortional buckling could be potentially double-counted if the local strength is based on such a stub-column result.

To study the phenomenon more deeply, a series of a selected cross-section with relatively low P_{nd}/P_{nl} ratio has been experimentally examined to determine the response of the stub column and to shed light on the local versus distortional behavior of the stub column and provide recommendations on how to better test stub columns for local buckling.

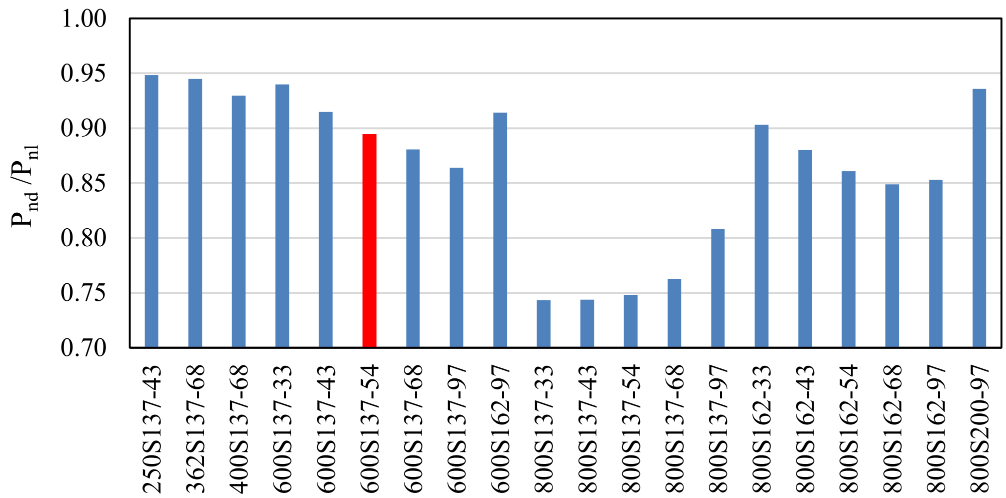


Figure 1: P_{nd}/P_{nl} ratios for lipped channel stub columns. Note: 600S137-54 (red bar chart) is selected for the tests.

3. Test specimen design

The cross-section of the stub columns in the experimental program has been selected based on having $P_{nd}/P_{nL}<1$ and the popularity of the cross-section as a vertical stud under pure compression. Accordingly, a 600S137-54 lipped C-channel has been selected to perform the tests. This cross-section was previously tested in DSM beam-column studies (Torabian and Schafer 2018).

Table 1: Effect of boundary condition on the P_{nd}/P_{nL}

	Simple-Simple	Clamped-Clamped
Length	18 in.	18 in.
P_{ne}	22.9 kips	24.6 kips
λ_l	1.78	1.82
P_{nL}	13.1 kips	14.0 kips
λ_d	1.89	1.49
P_{nd}	11.5 kips	13.4 kips
P_n	11.5 kips	13.4 kips
P_{nd}/P_{nL}	0.88	0.96

Since it is expected to observe distortional buckling prior to local buckling in an 18 in. ($3D_{web}$) long stub column of a 600S137-54, different specimens of the same length have been tested to exercise the effect of boundary conditions on the behavior of the stub column. This idea originates from the known effect of boundary conditions observed in DSM calculations, as shown in Table 1. Changing the end boundary conditions of a stub column from simple-simple to clamped-clamped, can potentially boost the elastic distortional buckling load (depending on length) and restraining end warping, as has been observed in the previous column tests of cold-formed steel columns with bare ends (Moen 2008).

The length of a column is an important parameter that can effectively change the distortional buckling capacity. Effect of length on the global buckling of a column is well known, and the Euler buckling load of columns is proportionally changing by $1/L^2$ in flexure, where L is the total length of the column with simple-simple boundary conditions. The effect of boundary conditions is traditionally considered using an effective length factor, K, and for the Euler buckling load is proportionally changing by $1/(KL)^2$. Similar behavior can also be considered for distortional and local buckling loads. If the length of the member is shorter than the length required for distortional and local buckling waves to happen, a boost in the buckling loads will occur. Since the local buckling wavelength (L_{crL}) is typically short (~D_{web}), the boost in the buckling load rarely happens for local buckling, but it may happen for distortional buckling, especially in stub column, where the length of the stub column and the distortional half-wavelength are comparable. In particular, for simple-simple warping free ends column length must be greater than the distortional bucking half-wavelength (L_{crD} ~ 2-8D_{web} in a typical lipped channel) for there to be no influence of the length and end conditions – for other end conditions the length at which distortional buckling is sensitive to these effects is even longer.

To cover a wide variety of boundary conditions and length, eight different specimens of 600S137-54 lipped c-channel per Table 2 were tested.

Table 2: Test matrix

End Condition	Length (in.)	Description
Bare*	4.25	L_{crL}
Bare*	8.5	$2L_{crL}$
Bare*	12	L_{crD}
Bare	18	$3D_{web}$
In-track	18	$3D_{web}$
Hydro-Stone® ends	18	$3D_{web}$
Welded Endplates	18	$3D_{web}$
Relative constraints	18	$3D_{web}$

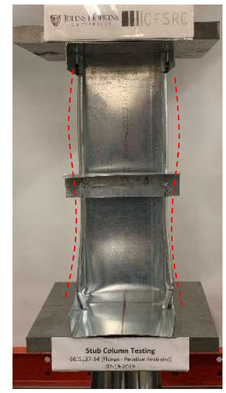
4. Test rig and testing procedure

All tests have been done with a hydraulic 100-kip MTS universal loading machine equipped with 12 in. × 12 in. × 1 in. loading platens in the Thin-walled Structures Laboratory at Johns Hopkins University. The load and displacements were taken from the LVDT and load cell of the loading equipment, and the actuator was controlled in displacement mode via an MTS 407 controller connected to the servo-valve. The centroid of the specimens was positioned at the center of the plates and the actuator. The loading rate was kept at 0.0083 in./second for these tests.

5. Test results

Results of the specimens with different end boundary conditions are provided in Table 3, and the results of variable length specimens are provided in Table 4. Comparing the results of specimens with different end conditions shows that the specimen with the welded end plate has the highest capacity of 14.2 kips, which was expected; however, the results are not significantly different from one another. Since variability in the test results is always expected, the direct effect of end conditions is hard to distinguish, and therefore, it would be reasonable to assume that the effect of end conditions is not pronounced in this study.

Table 3: 18 in. test specimens at and after the maximum load P_{max}

				
Bare ends L = 18 in. P_{max}= 13.9 kip	Welded end plates L = 18 in. P_{max}= 14.2 kip	In-track ends L = 18 in. P_{max}= 13.6 kip	Hydro-Stone® ends L = 18 in. P_{max}=13.1 kip	Relative flange Constraints* L = 18 in. P_{max}= 13.9 kip

* The flange deformed shape is similar to the second distortional buckling mode due to the use of relative flange constraints.

Table 4: Variable length test specimens at and after the maximum load P_{max}

			
Bare ends* L = 18 in. P_{max}= 13.9 kip	Bare ends L = 12 in. P_{max}= 13.6 kip	Bare ends L = 8.5 in. P_{max}= 18.6 kip	Bare ends L = 4.25 in. P_{max}=19.3 kip

* This specimen is first shown in Table 3 but shown here as well to make comparison easier.

Table 4 summarizes the results of specimens with different lengths: 18, 12, 8.5, and 4.25 in. and bare end boundary conditions. The results show that the length can switch the buckling mode and increase the capacity of the stub columns. While 18- and 12-in. specimens still failed in restrained distortional buckling, no distortional buckling was observed in the 8.5 in. and 4.25-in. long specimens. Instead, flange and web local buckling was observed in the shorter specimens. It should be noted that the distortional half-wave length of the 600S137-54 lipped channel tested here is 12 in., and the results show when the tested length is shorter than 12 in. the distortional buckling capacity will be boosted, and therefore, local buckling can happen prior to distortional buckling.

Figures 2 and 3 provide the load-deformation response of the tested stub column specimens. The results in Figure 3 have been corrected for the initial anomaly due to the end condition and bearing development.

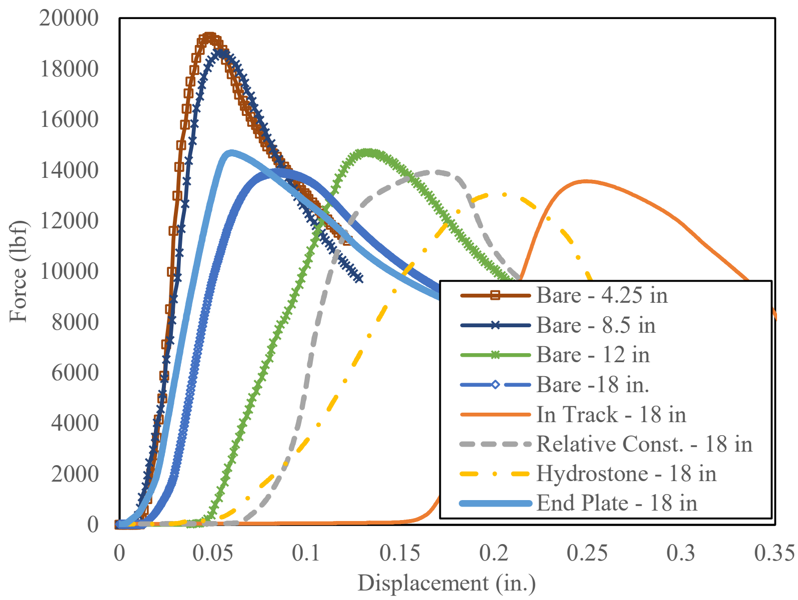


Figure 2: Load-deformation response of tested stub column specimens (raw data)

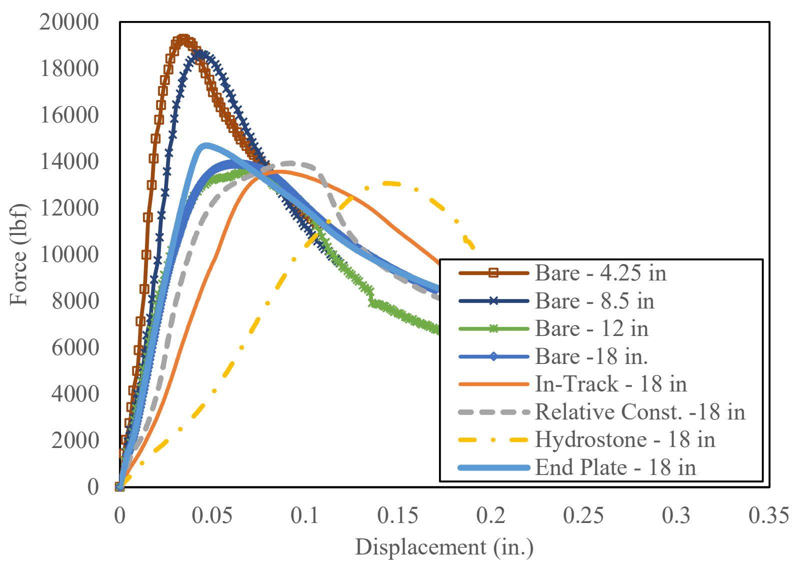


Figure 3: Load-deformation response of tested stub column specimens (corrected for the initial anomaly due to the end condition and bearing development)

The load-deformation response show that the initial stiffness of stub columns can be influenced by the end contact conditions. The specimen placed in Hydrostone, and the specimen tested with top and bottom tracks, had lower initial stiffness compared to the other specimens with either bare or welded end conditions. The shorter specimens have higher stiffness, simply due to shorter length of the specimen, but those specimens shorter than the distortional half-wavelength (4.24 and 8.5 in. specimens) had higher axial stiffness up until local buckling of the specimens.

6. Discussion

For a specimen that meets the length for testing as a stub column, regardless of end conditions, the maximum load was in the same range, and the observed mode of buckling was distortional buckling. Accordingly, the end conditions did not significantly change the capacity/mode of buckling, and the increased strength due to the most fixed end conditions was not sufficient to preclude distortional buckling and trigger local buckling in the tested stub columns. For specimens with lengths shorter than allowed by stub column test standards, it was shown that length does have a significant effect on restraining the distortional mode, and local buckling was eventually observed.

In this regard, we have a tension between the desire to have a short specimen that precludes distortional buckling but not short as to artificially boost local buckling. The “suggested lengths” provided by AISI-S902-17 do not consider distortional buckling and do not successfully ensure local buckling controls in tested stub columns. The mode shift provided by changing the end conditions is not enough to isolate local buckling and distortional buckling. Therefore, the length of the specimens needs to be determined based on the expected behavior of the specimens and the desired mode of failure. The signature curve of the stub column can be potentially used to associate the length of the stub column with the mechanical characteristics of the specimen. As shown in Figure 4, the suggested length of 18 inches in AISI-S902-17, is longer than the distortional half-wavelength of 12 in. in the 600S137-54. As observed in the experimental program, the length of the stub column needs to be shorter than the distortional half-wavelength to boost the distortional capacity of the member and avoid distortional failures. Accordingly, the suggested length of the stub column to ensure local buckling happens prior to distortional buckling should be closer to:

$$1.25L_{crl} < L < 0.8L_{crd} \qquad (1)$$

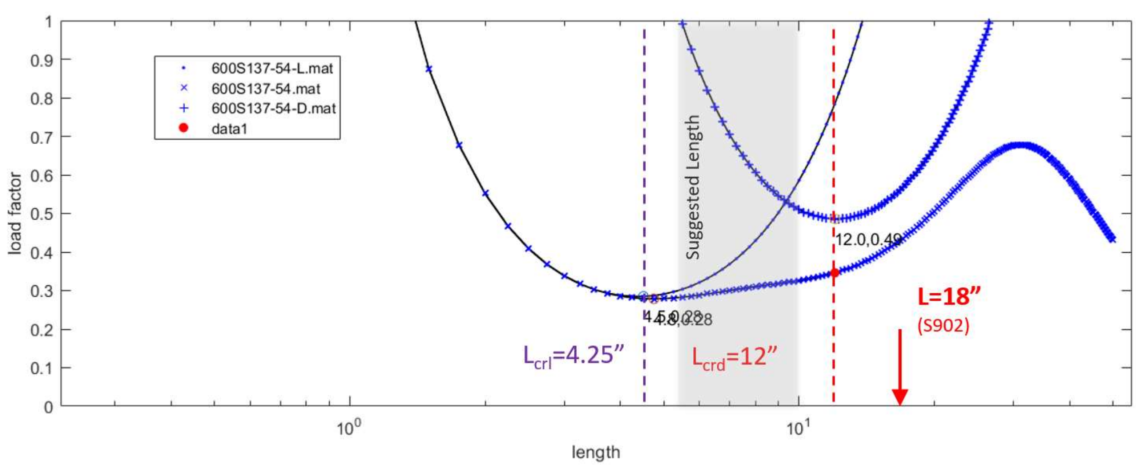


Figure 4: 600S137-54 signature curve by CUFSM 5.04

To examine if the suggested length is reasonable and applicable to lipped channel cross-sections, the local and distortional half-wavelengths have been determined for all SFIA lipped channel cross-sections, and the suggested length limits are shown in Figure 5. The results have shown the suggested length is reasonable for almost all cross-sections. It is worth noting that the specimens are considerably shorter than current practice.

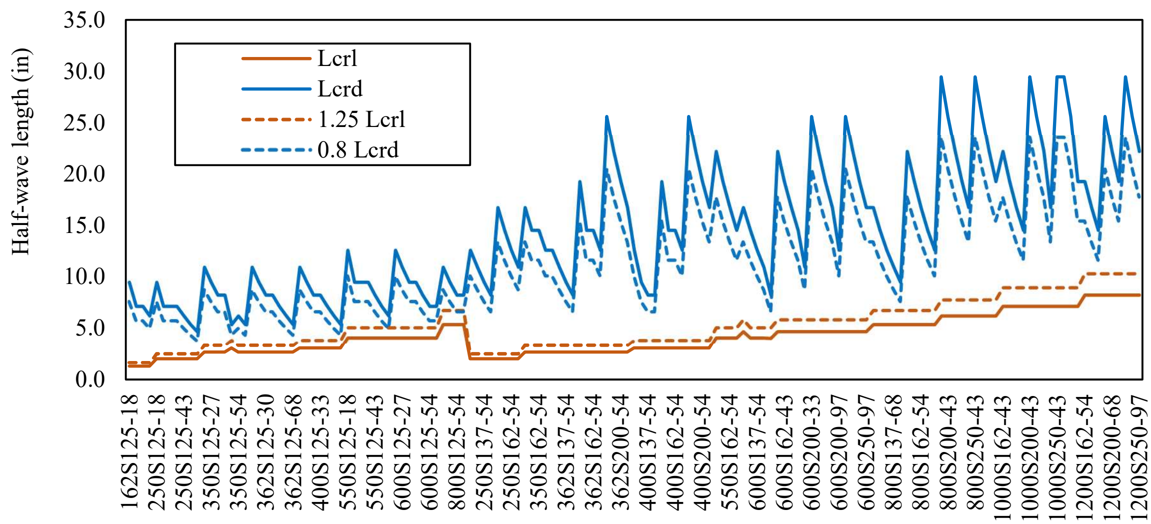


Figure 5: Suggested length limits for all lipped channel cross-sections

The adequacy of the proposed length limitations for stub column testing has also been studied for a rack cross-section as well and will be reported in the future.

7. Conclusions

The appropriateness of length requirements in cold-formed steel stub column testing standards has been investigated via experimental and analytical studies on lipped channel sections. The results have shown that the current length requirements, which are mostly associated with the geometrical dimension of the cross-section, do not ensure the failure mode in the test to be local buckling. Thus, the current testing method underestimates the effective area for local buckling of the columns as it incorporates other failure modes in its reduction. Examining different techniques to boost distortional buckling, and remove its influence from the testing, it was found that the length of the stub column needs to be shorter than the distortional buckling half-wavelength Since, only lipped channels are studied herein, further experimental and analytical studies on different types of cross-section including rack cross-section with different hole patterns in the web and flange is required to confirm the concept, and the suggested lengths for the stub columns.

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