Virtual testing against experiment for post-buckling behaviour of cold-formed steel columns

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Abstract

Cold-formed steel has already started to replace hot rolled companions in some structural applications. Advantages of cold-formed steel originate from its high strength over weight ratio and ease of manufacturing and construction compared to hot rolled heavy sections. Moreover, cold-formed columns have significant post-buckling reserve which has the potential to be exploited in design process. Therefore, it is essential to predict the response of cold-formed columns by means of high fidelity engineering techniques. Herein an in depth study which links experimental testing and non-linear computational capabilities is undertaken to address the failure behaviour of cold-formed columns. Experimental program comprises coupon tests to specify material properties and compression testing of fixed end cold-formed columns. Thereafter, measured material properties are utilized to generate a stress-strain curve for finite element models. Boundary conditions imposed into simulation models in such a way that would represent test conditions. Creating a suitable mesh for different cross sectional dimensions, different shapes of initial imperfections are introduced into models to compare contributions to performance of columns. Predicted collapse loads and modes via finite element models are assessed against test results. Mesh and initial imperfection sensitivities on failure characteristics are discussed. Finally a general assessment is made for the deployed testing and simulation to generate knowledge for the design evaluation of cold-formed steel columns. Key findings and discussions of present study have the potential to lead to develop promising cold-formed steel column virtual test models.

Introduction

Cold-formed steel structures is rapidly gaining acceptance in field of structural engineering due to its advantageous characteristics such as ease of manufacturing and construction and high strength over weight ratio of individual structural elements. In order to satisfy increasing requirements of structural engineering and cold-formed steel applications numerous researches were undertaken. Research into cold-formed steel goes back to the works presented by Cornell University in 1940s [1, 2]. In further decades many investigations were performed on account of promising characteristics of cold-formed steel [3-5].

Cold-formed steel operates in field of thin-walled structures in which instability is of great importance. Formation of buckling in cold-formed steel elements may invite premature failure in assembled structure. Therefore, to develop safe designs buckling behaviour of these thin-walled structures must be delineated in detail. Since thin plate elements constitute cold-formed sections, plate buckling theory is employed in evaluation processes [6]. As is well known, determination of plate buckling requires the integration of wide variety of failure modes such as global and local ones. Moreover, noticeable post-buckling reserves of plate elements must be accounted for in performance evaluation of cold-formed steel elements. So, nature of complexity of response calls for advanced non-linear approaches to be utilized in designs. Theoretical empirical formulations developed in the past to evaluate performance of cold-formed steel sections. These formulations rely on effective plate width approaches which were proposed as a result of extensive theoretical and experimental investigations [7-9]. The North American design specification AISI-2007 [6] also employs effective width method to determine performances of cold-formed members under compression. Unfortunately empirical methods have limitations in terms of material properties and geometrical configurations. Thus, experimental testing and advanced numerical modelling have become main research tools in field of cold-formed steel [10-12].

Present study particularly concerns with assessment of numerical models against testing to evaluate compression performance of cold-formed columns. Experimental part of the study consists of testing of two Unstiffened Channel (UC) columns having different geometrical configurations and coupon tests to specify material properties. Having captured the behaviour of test specimens numerical models are developed using commercial Finite Element (FE) package ANSYS. Aiming at tracing best representative virtual test models for columns, various FE models are considered with different mesh densities and geometrical imperfections. The performances of all models are assessed against test results and significant key details are presented. Key findings and discussions of present study show the sensitivity of cold-formed columns and have the potential to lead to develop promising cold-formed steel column virtual test models.

Test specimens

Roll-forming, brake-pressing and bend-pressing are available methods to produce cold-formed steel members in practice In present study two test specimens were produced using brake pressing method. Table 1 presents the details of geometrical configurations of test specimens and Figure 1 depicts corresponding conventions.

Table 1 Dimensional detail of specimens (mm)

Specimen	b_0	h_0	R	t
UC 80-30	77.95	33.07	3.0	0.9
UC 80-50	79.52	53.35	3.0	0.9

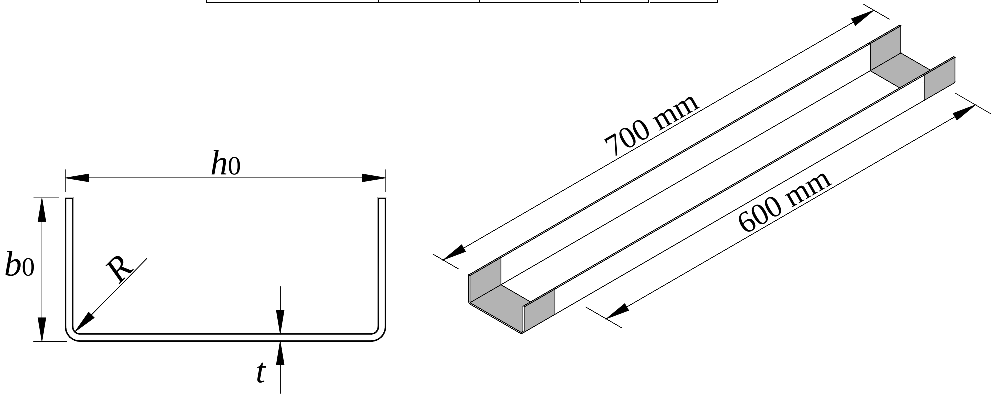


Figure 7 Geometrical configuration

Length of 600 mm for test specimens was considered to permit observation of coupled instabilities in post-buckling ranges such as combined local and global modes of failure. Prior to testing both specimens were marked to monitor failure modes clearly. Boundary conditions of specimens were designed to provide fully clamped end restraints. To provide such a boundary condition 50 mm thick epoxy resin bases were cast on to top and bottom ends of the specimens (shaded areas in Figure 1). A displacement controlled loading with slow rates was applied to column specimens in testing machine to simulate static loading conditions. The behaviours of columns in pre-buckling, buckling, post-buckling and failure ranges were monitored to provide reference data for virtual test assessments.

Three coupon tests also were undertaken to specify steel material properties. Test results indicate that the quality of used material corresponds to S235 steel as expected.

Virtual test models

Virtual test models of specimens were developed using commercial FE package ANSYS. Since the column specimens are thin-walled members, shell elements are appropriate to deploy into modelling of cold-formed columns. Shell181 shell element was employed for this purpose. Shell181 is suitable for analysing thin to moderately thick structures. It is a four node element with six degrees of freedom at each node [13].

Geometric and material non-linear properties of Shell181 element were activated during numerical simulations. Since stress-strain diagram of carbon steel has definite yield point and yield plateau, elastic perfectly plastic material model is deemed appropriate to obtain satisfactory results. So, an elastic perfectly plastic material model with an elastic modulus of 206 GPa was introduced into FE models.

As is well known, magnitude and shape of initial imperfections influences the failure characteristics of thin-walled structures such collapse load and failure mode shape. Unfortunately there exist no opportunity to measure such imperfections of laboratory specimens. Therefore, a common experience available in literature was followed to develop imperfect models. According to this approach initial buckling modes of models can be utilized as shape of geometrical imperfections. And most common is to employ 1st local buckling mode for this purpose. In present study various initial buckling modes with different magnitudes were introduced to generate geometrical imperfections. Thus, magnitude and shape sensitivities of initial geometrical imperfections were treated in detail. Also in a further phase the mesh densities of column models were changed to exhibit the effects on failure behaviours. Table 2 and Figure 2 provide the details of developed virtual test models in present study.

Imperfection sensitivity phase of virtual tests was undertaken employing models with medium mesh densities as indicated in Figure 2. For the mesh sensitivity part of the study 1st buckling modes of columns with magnitude of 10 % thickness were incorporated into models as initial geometrical imperfections.

Table 2 Shapes and magnitudes of initial geometrical imperfections

Virtual model	Imperfection shapes and magnitudes (in terms of column thickness)					
	1st mode		2nd mode		3rd mode	
UC 80-30-0.9	10 %	100 %	10 %	100%	10 %	100 %
UC 80-50-0.9	10 %	100 %	10 %	100 %	10 %	100 %

Boundary conditions of FE models are created in such a way that would represent specimens' fully clamped boundary conditions. Also displacement controlled Newton-Raphson method was used in FE analysis process of virtual test models.

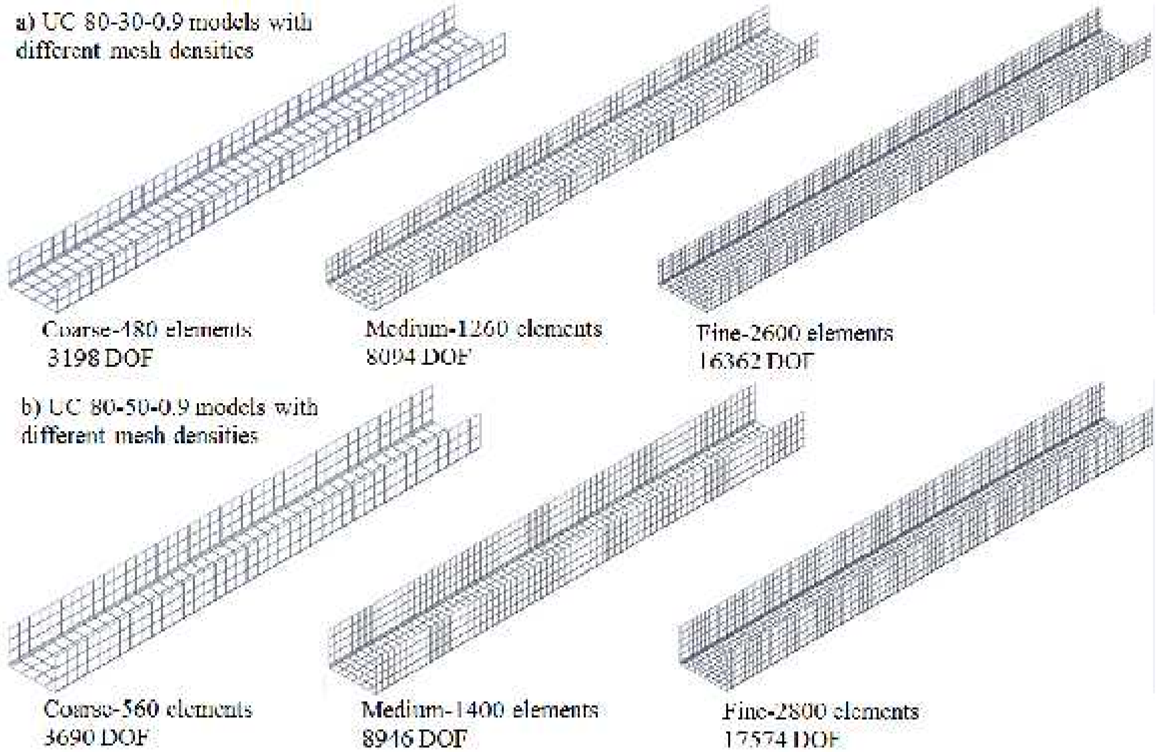


Figure 2 Mesh densities of virtual test models

Virtual test against experiment

Figure 3 provides the collapse mode shapes of test specimens. Both specimens failed in a combined local and global mode as expected.

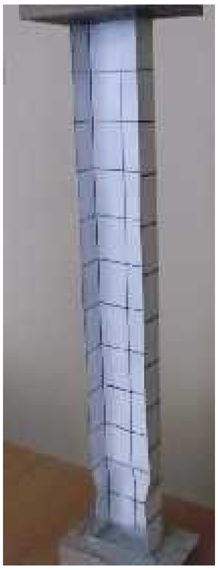
a)  b) 

Figure 3 Collapse modes of test specimens a) UC 80-30 b) UC 80-50

During the tests, specimen boundaries acted as fixed supports as designed before testing. Load displacement curves of specimens were recorded during the tests using equipment of testing machine and presented in following figures. Collapse loads of specimens were measured to be 15.66 kN and 18.12 kN for specimens UC 80-30 and UC 80-50 respectively.

Focusing on shape and magnitude of initial geometrical imperfections Figure 4 presents the load displacement curves of virtual test models against the curves obtained from UC 80-30 laboratory tests. In these figures to present a clear vision only minimum and maximum performances obtained from virtual tests are presented. Collapse loads and mode shapes resulted from six simulations for UC 80-30 are shown in Figure 5.

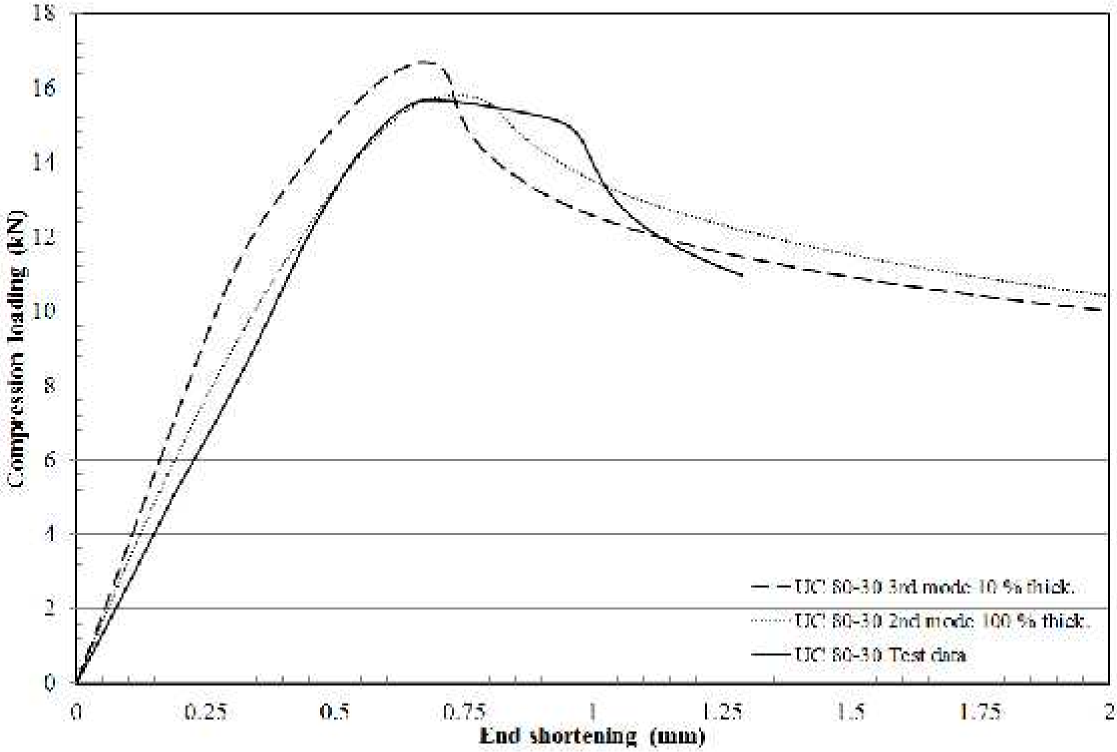


Figure 4 Load vs. end shortening curves for UC 80-30 (imperfection sensitivity)

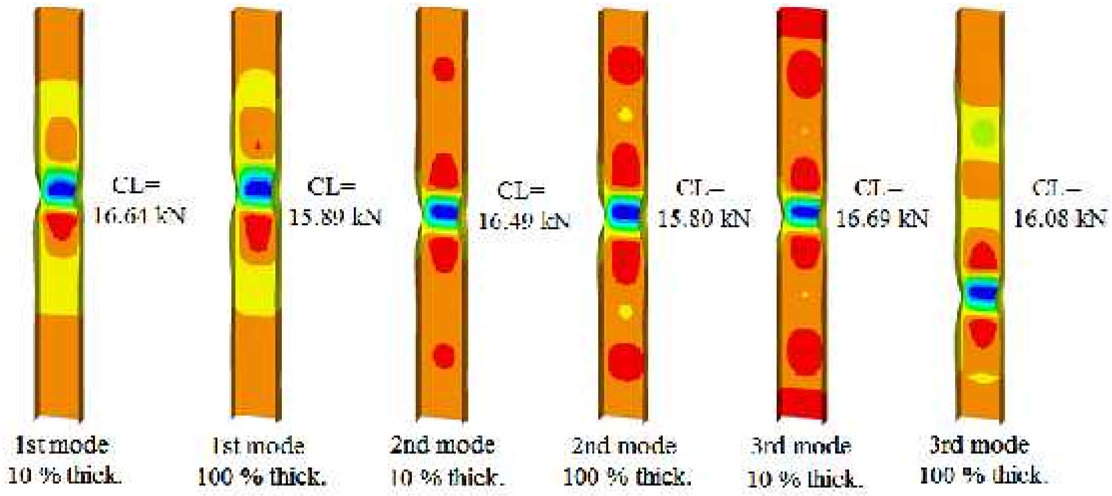


Figure 5 Effects of imperfection shape and magnitude on collapse mode shape of UC 80-30

Figures 4 and 5 indicate imperfection sensitivity of UC 80-30. Predicted collapse loads for UC 80-30 are within 5.4 % of each other. And the model with initial imperfection shape of 2nd buckling mode and with magnitude of 100 % column thickness exhibited best performance in predicting collapse load of specimen UC 80-30. This virtual model has only 0.83 % greater collapse load compared to performance of test specimen. Also the shift in initial stiffness in Figure 4 as a result of differences in geometrical imperfections underlines the potential sensitivity of cold-formed columns to initial production defects. Moreover, collapse modes of six virtual tests presented in Figure 5 confirm this sensitivity. Geometrical imperfections of test specimens could not be measured as detailed in previous section. Herein it is worth noting that employment of initial buckling modes with magnitudes of the order of column thickness leads to satisfactory collapse load results. However, good prediction of collapse mode shape requires the imperfections of field specimen to be measured and employed in virtual test.

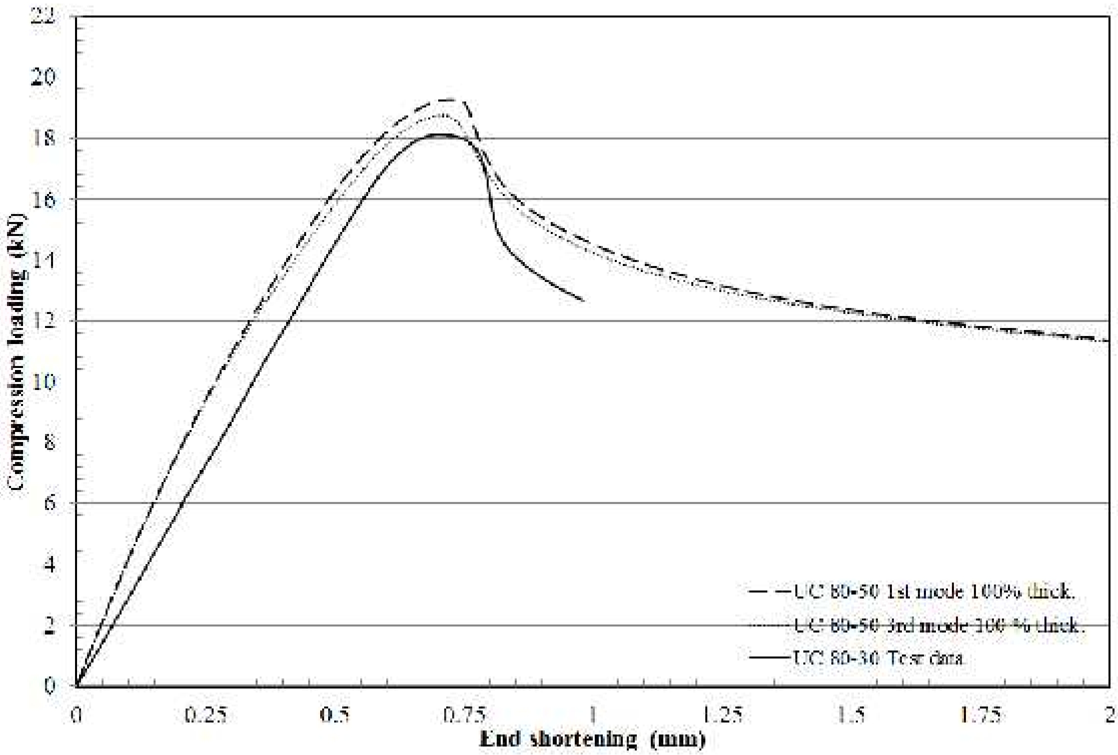


Figure 6 Load vs. end shortening curves for UC 80-50 (imperfection sensitivity)

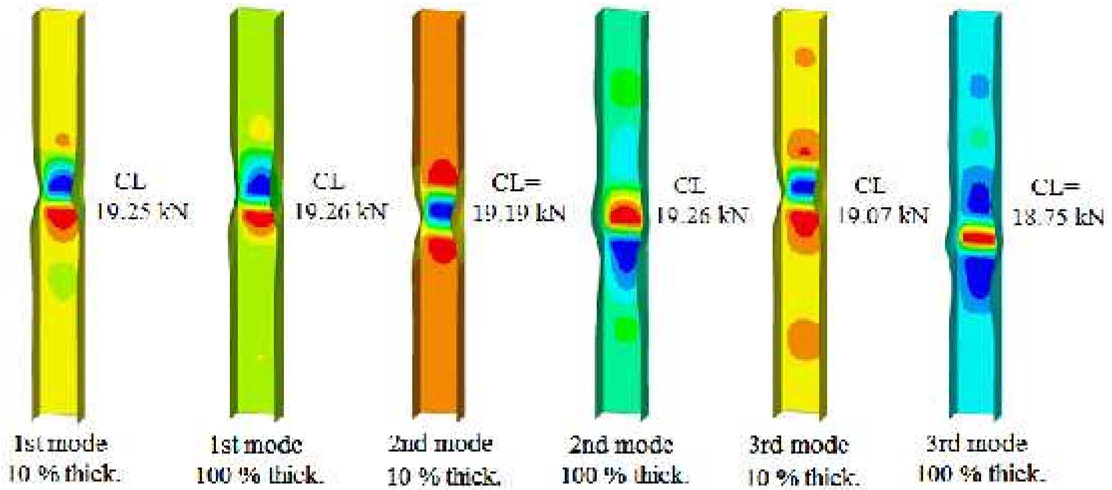


Figure 7 Effects of imperfection shape and magnitude on collapse mode shape of UC 80-50

Figure 6 suggests that imperfection sensitivity of collapse load of specimen UC 80-50 is not as much as the sensitivity of specimen UC 80-30. 2.72 % scatter in predicted collapse loads implies this behaviour. Also very close initial stiffness of virtual test models depicted in Figure 6 provides another support for less imperfection sensitivity of column performance. Among the performed six simulations, the best predicts 3.47 % greater collapse load compared to performance of test specimen. This indicates a probable greater magnitude of geometrical imperfection of specimen UC 80-50. Although scatter in predicted loads is narrow for this model, resulted collapse mode shapes are very different as shown in Figure 7. This again shows the importance of specimen imperfections in prediction of collapse shape.

Figure 8 and 9 provide the responses of model UC 80-30 to FE mesh sensitivity. Load displacement curves and collapse mode shapes depicted in figures indicate discrepancies as a result of employing different meshes for same geometrical configuration.

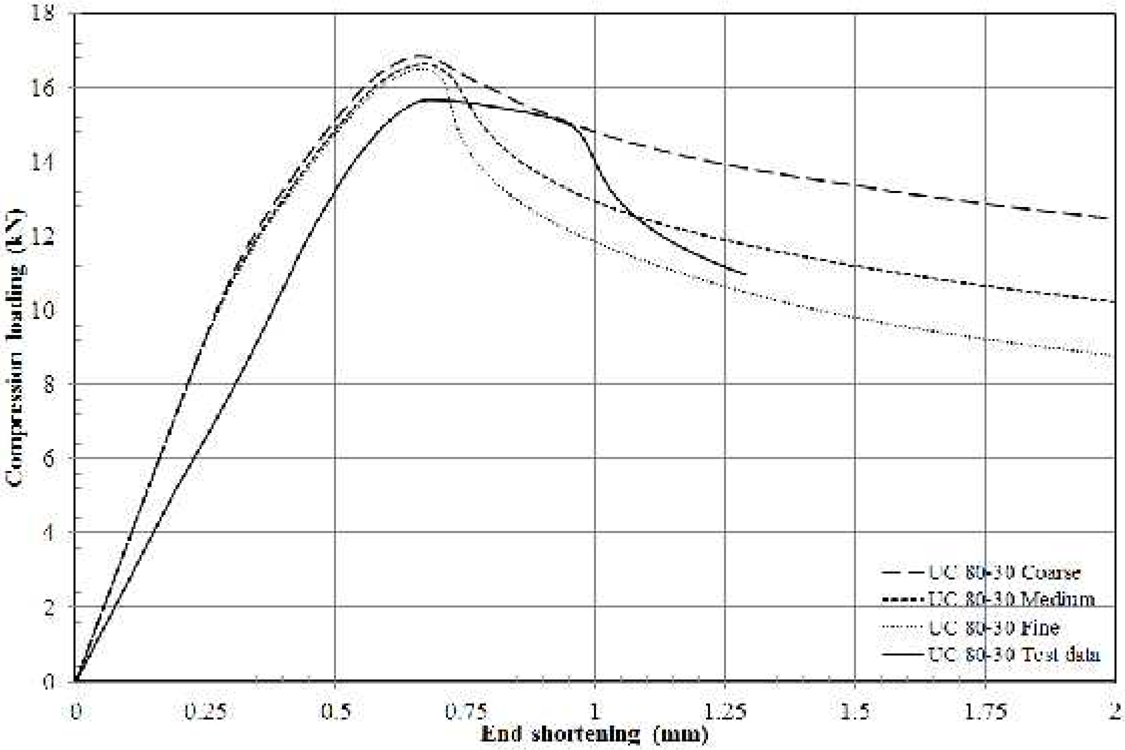


Figure 8 Load vs. end shortening curves for UC 80-30 (mesh sensitivity)

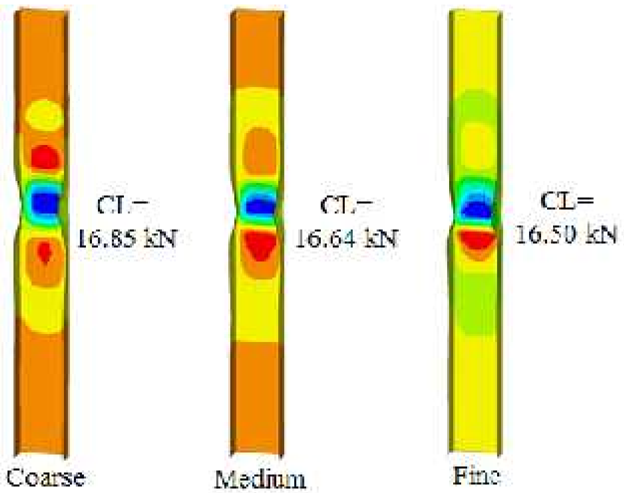


Figure 9 Effects of mesh density on collapse mode shape of UC 80-30

Figure 8 reveals that influence of representative mesh on collapse load of model UC 80-30 is small. The scatter in predicted collapse loads is just 2.12 %. However, the response of virtual models beyond the collapse significantly differs as shown in Figure 8. Examining Figure 9 it can be observed that mesh density brings about moderate level of differences in collapse mode shapes.

For specimen UC 80-50 sensitivity of the configuration to mesh density is indicated in Figures 10 and 11.

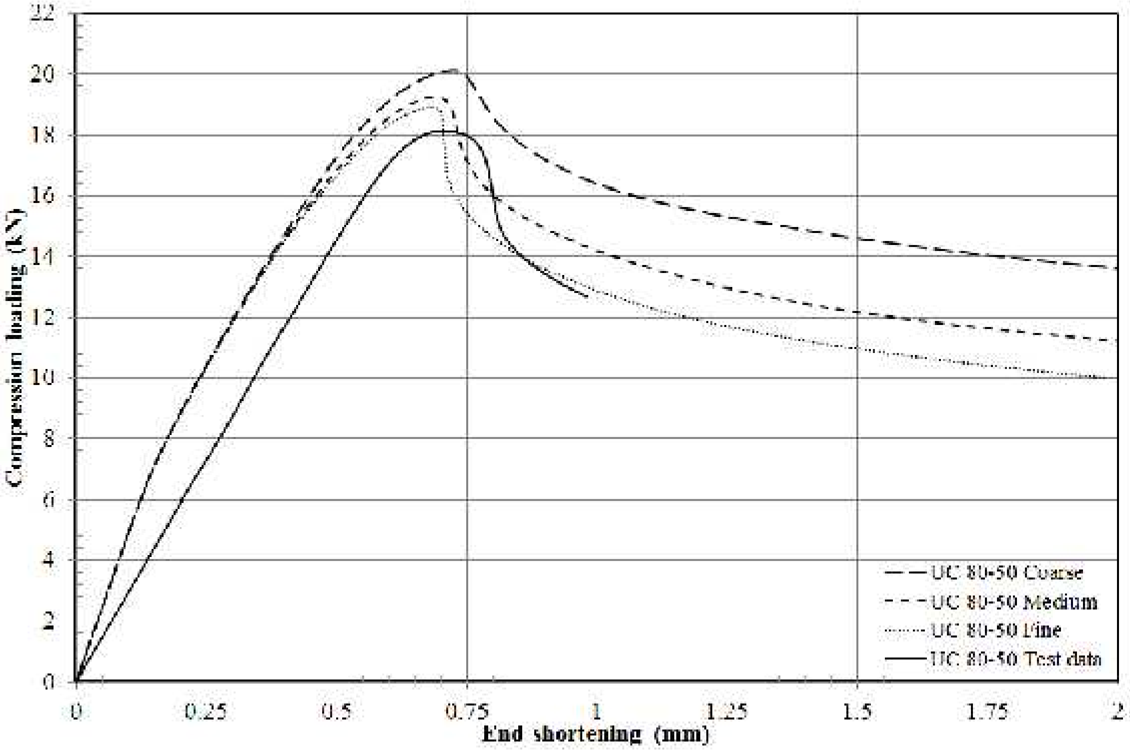


Figure 10 Load vs. end shortening curves for UC 80-50 (mesh sensitivity)

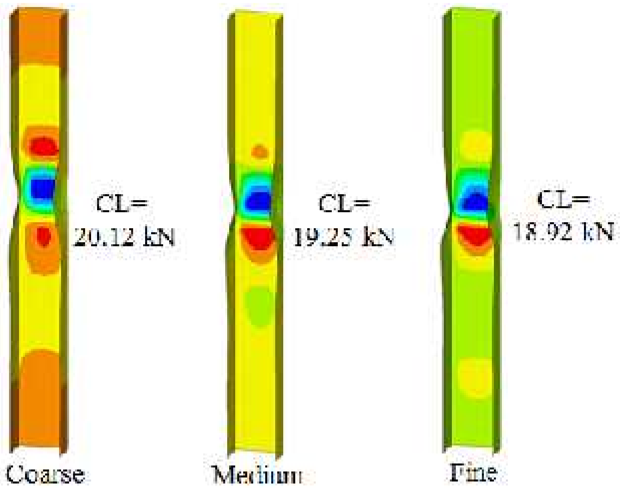


Figure 11 Effects of mesh density on collapse mode shape of UC 80-50

As opposed to model UC 80-30, model UC 80-50 was found to be mesh sensitive as shown in Figure 10. Collapse loads of models with different meshes spread out into a 6.34 % scatter. Again significant differences in stiffness of models beyond the collapse were exhibited, Figure 10. Depicted shapes in Figure 11 again imply moderate level of mesh sensitivity of collapse mode shapes.

Conclusions

The experimental and simulation works presented in this paper confirmed that initial geometrical imperfections and unrepresentative meshes have the potential to compromise performance of cold-formed column virtual models. Representative virtual test models can be developed for cold-formed columns by accounting for all geometrical and material characteristics of specimen under consideration. To provide the key findings of present work in a more definite format, followings conclusions can be drawn;

- Having determined the shape and magnitude of real geometrical imperfections, a mesh sensitivity study must be undertaken to capture rational behaviours.
- The sensitivity of specimen to geometrical imperfections and mesh density entirely depend on geometrical configuration. In present work UC 80-30 was found to be more imperfection sensitive whereas UC 80-50 exhibited a mesh sensitive behaviour.
- The shape of initial buckling modes can be employed to predict collapse performance of specimens in absence of real geometrical imperfection data. But this method calls for great care and needs various buckling modes to be considered. Because as shown in figures 1st buckling mode shape may not be the most detrimental one.
- Although collapse loads of cold-formed columns can be closely approached by experiencing initial buckling mode shapes as geometrical imperfections with magnitudes of the order of column thickness, good prediction of collapse mode shape definitely requires incorporation of measured imperfections into FE models.
- The greater magnitude of imperfection does not always cause reductions in collapse loads of cold-formed steel columns when local shapes of imperfections are under consideration, Figures 5 and 7.

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