FINITE ELEMENT ANALYSIS OF THE CYCLIC BEHAVIOR OF CIRCULAR TUBULAR BRACES

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To address the concerns of cyclic behavior of braced frames. This paper is focused on the plasticity model of finite element analysis for concentric braces. FEA using the cyclic constitutive model with nonlinear kinematic hardening were carried out to simulate the cyclic behaviors of the existing test results. The constitutive model provides close predictions with various parameters such as slenderness ratio, diameter to thickness ratio and material properties. Using the simple hardening rule decided by the yield and tensile strength of the monotonic material tests, the discussion is presented to explain the behavior of braces with flexural and local buckling under cyclic loadings.

Keywords: Circular hollow section; Steel brace; Cyclic behavior; Flexural buckling; Local Buckling

1 Introduction

Circular hollow sections are used in building structures as braces. The brace buckling of plastic hinges at mid-length are affected by the process of manufacturing cold-formed and hot-rolled hollow structural sections. The experimental results of the CHS braces are not enough to evaluate the requirements for cyclic behaviors changing with varied material properties by manufacturing process and it is important to study the plastic behavior with local buckling and brittle fracture characteristics under cyclic loading.

The purpose of this paper is to demonstrate the validity of the FE model using the cyclic constitutive model with nonlinear kinematic hardening and to compare the hysteresis behavior of cold-formed and hot-rolled circular hollow sections under cyclic loading. Differences of behavior of the members under cyclic loading with forming processes of the sections are discussed with FE results.

2 Numerical Simulation

2.1 *Finite Element Analysis Modeling*

The nonlinear finite element analysis software package ANSYS is adopted to develop a nonlinear finite element model to capture the structural behavior of concentric braces under cyclic loading. Three-dimensional 8-node solid-shell element is used for circular hollow sections of the braces. The Solid-shell element possesses the continuum solid element topology and features eight-node connectivity with three degrees of freedom at each node. Also, the element

Proceedings of the 17th International Symposium on Tubular Structures.
Editors: X.D. Qian and Y.S. Choo

Published by Research Publishing, Singapore.
ISBN: 978-981-11-0745-0; doi:10.3850/978-981-11-0745-0_083-cd

defines layered section in the thickness direction. Therefore it accurately calculates the stress field in the thickness direction. The element is a 3-D solid element free of Poisson thickness locking in bending-dominant situations.

Loading method and boundary conditions to simulate the axial cyclic loading performance of the CHS braces are shown in Figure 1. As a boundary condition, the end of the model is one-sided pin support and the other is a roller support. Also, the loading method is a horizontal displacement control at the roller support.

Typical Finite element mesh developed using ANSYS with solid-shell elements is shown in Figure 2. The overall meshes with elements of size equal to 20mm were found to provide reliable results in the analysis.

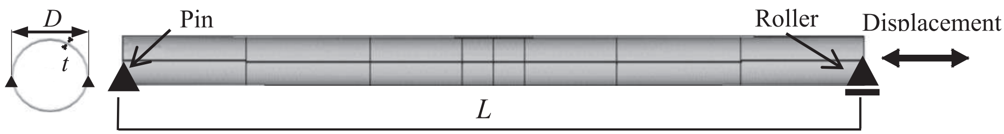


Figure 1. Dimensions and Boundary condition

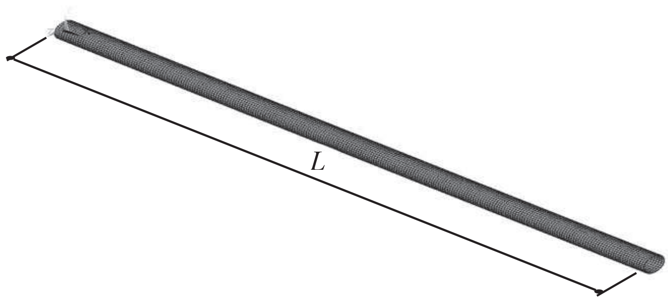


Figure 2. Finite element mesh

2.2 *Plasticity Model*

The Von Mises yield criterion with nonlinear kinematic hardening rule is used in this study. The characteristics of the Chaboche model are determined by the C and γ values as shown in Equation 1. The kinematic hardening components are described by a sum of several back stresses with different independent evolution rules as;

$$\alpha = \sum_{i=1}^{n} \alpha_i \,, \qquad \dot{\alpha}_i = \frac{2}{3} C_i \dot{\varepsilon}_p - \gamma_i \alpha_i \lambda \tag{1}$$

where α_i and n =i th back stress and total number of back stresses; C_i = initial hardening module; ε_{pl} = equivalent plastic strain; γ_i=nonlinear recovery parameter and λ= incremental accumulated plastic strain.

The Von Mises yield criteria can be expressed as follows:

$$f = \sqrt{\frac{3}{2}(s-\alpha):(s-\alpha)} - R = 0 \tag{2}$$

where s = deviatoric stress; α= back stress and R = size of yield surface which is constant in the kinematic hardening models.

Model parameters of two back stresses determined by properties of tensile coupon tests are proposed. The first term α_1 with C_1 and γ_1 cover a stress range from beginning of yielding R to nominal tensile strength σ_u. The second term α_2 with C_2 and γ_2 is used to model as the final linear part at true stress after tensile strength. These back stresses can be given as follows;

$$\alpha_1 = \sigma_\mathrm{u} - R \tag{3}$$

$$\alpha_2 = \sigma_\mathrm{u}^* - \sigma_\mathrm{u} = \varepsilon_\mathrm{u}\sigma_\mathrm{u} \tag{4}$$

where ε_u = logarithmic plastic strain at tensile strength and σ_u^* = true stress of tensile strength.

Initial yielding stress R is lower than the stress σ_y at 0.2% permanent strain of cold formed sections, which is accounted as;

$$R = \sigma_\mathrm{y} \cdot \mathrm{YR} \tag{5}$$

where YR = yield ratio.

Initial hardening module of first term for cold formed section can be assumed as

$$C_1 = \frac{E}{20} \cdot \frac{\sigma_u}{\sigma_y} \tag{6}$$

The yield stress with yielding plateau for hot rolled section is used as the size of yield surface, which is assumed as follows;

$$R = \sigma_y \tag{7}$$

Initial hardening module for hot rolled section can be given as

$$C_1 = \frac{E}{50} \cdot \frac{\sigma_u}{\sigma_y} \tag{8}$$

The first back stress for all sections is formulated as;

$$\alpha_1 = \frac{C_1}{\gamma_1} = \sigma_u - R \tag{9}$$

Nonlinear recovery parameter is decided by yield strength and initial yield stress as;

$$\gamma_1 = \frac{C_1}{\sigma_u - R} \tag{10}$$

The second term α_2 is used to model as the final linear part at true stress after maximum tensile strength. It was assumed that the difference between engineering stress and true stress at tensile strength equal to second back stress. Through using the elongation at maximum strength, tensile strength and the modulus at tensile strength assumed as 1/2 σ_u^*, C_2 can be calculated by using the following equation;

$$C_2 = \left\{\frac{1}{2} + \left(\frac{1}{2} + \gamma_2\right)\varepsilon_u\right\}\sigma_u \tag{11}$$

The plasticity model and corresponding approach to calibrate the model parameters with manufacturing process on mechanical properties of cold-formed and hot-rolled sections are employed in this study. It is difficult to decide actual elongation ε_u by tensile coupon test results with various materials. Also, this parameter is not so sensitive for the back stress.

In this paper, it is assumed that ε_u is defined as 5% with cold-formed and 15% with hot-rolled.

3 Experimental Data and FE Results

3.1 *Slenderness ratio and Diameter to Thickness ratio*

FEM is performed on cold-formed CHS braces subjected to cyclic loading, and the validity of the FE model is examined in comparison with the results of the previous experimental data by Matsumoto (1987). Table 1 shows dimensions and material properties in experimental data. CHS braces of $60 \leqq \lambda \leqq 80$ and $40 \leqq D/t \leqq 60$ were selected to investigate the effects of local buckling, flexural buckling of the braces.

Table 1. Dimensions and Material properties of experimental data

Specimen	D/t	λ	D (mm)	t (mm)	L (mm)	A (mm²)	tensile coupon test		Young's modulus (N/mm²)
							σ_y (N/mm²)	σ_u (N/mm²)	
60-80-1,2,3	61.1	80.7	267.8	4.38	7513	3625	457	528	213000
50-80-1	50.0	82.6	214.7	4.29	6145	2836	338	443	210000
50-60-1	50.0	61.3	214.2	4.28	4550	2823	334	459	202000
40-60-1	39.4	60.4	216.8	5.50	4514	3651	394	478	225000

Material properties in Table 1 are used for determining the parameter for the Chaboche model showing in Table 2.

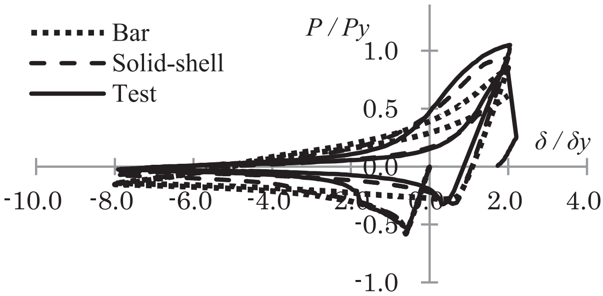
Table 2. Parameter for Chaboche model

Specimen	R (N/mm²)	C_1 (N/mm²)	γ_1	C_2 (N/mm²)	γ_2
60-80-1,2,3	395.5	12304.6	92.9	897.6	23.5
50-80-1	257.9	13761.8	74.3	753.1	23.5
50-60-1	243.0	13879.9	64.3	780.3	23.5
40-60-1	324.8	13648.5	89.1	812.6	23.5

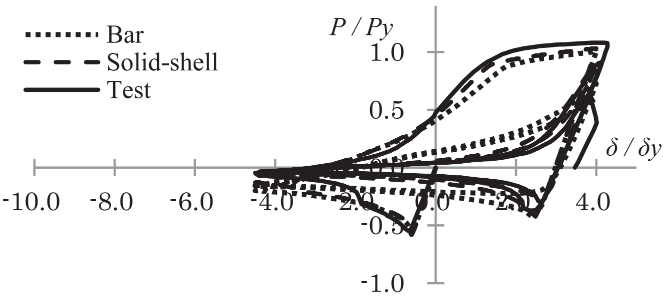
The relation between the load P/P_y (P_y; tensile yield strength of the section) and the deformation δ / δ_y (δ_y; elastic displacement of the brace at P_y) of the analysis result and the experimental data are shown in Figure 3.

The bar element can be used to model the structural elements only for flexural buckling, expansion and shrinkage of the brace deflections, not used for local buckling with sectional deformation. The solid-shell element can be used for local buckling behavior with distortion in the cross sectional shape. Figure 4 shows the deformation of the local buckling and cross-sectional flatness (60-80-3) of the FEM in the fifth compression cycle.

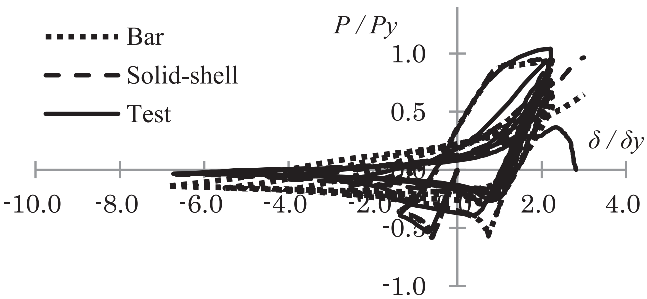
The FEA with Chaboche model used solid-shell element can accurately simulate the formation of the flexural buckling, the local buckling and the behavior at the tensile side under cyclic loadings.



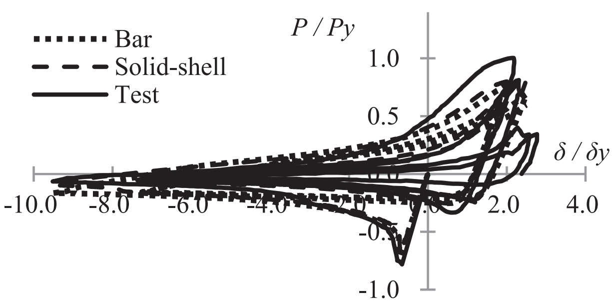
(a) 60-80-1



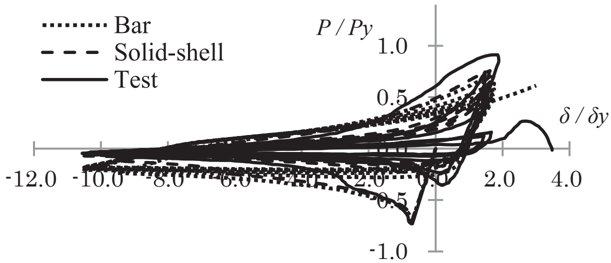
(b) 60-80-2



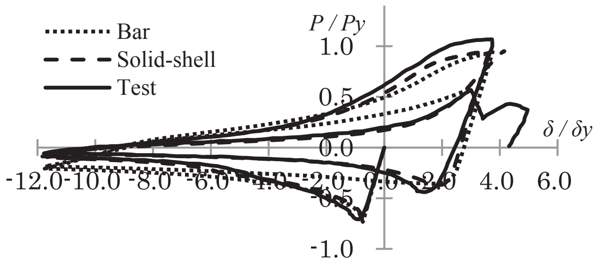
(c) 60-80-3



(d) 50-80-1



(e) 50-60-1



(f) 40-60-1

Figure 3. *P-δ* Curve

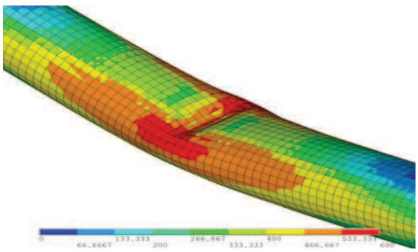


Figure 4. Local buckling

3.2 *Material Properties*

The Chaboche models of the stress-strain relationships are affected by the process of manufacturing cold-formed and hot-rolled hollow structural sections. This chapter is to compare the behavior of cold-formed and hot-rolled hollow structural sections under cyclic loading as obtained FEA results. Table 3 shows dimensions and material properties of experimental data by Packer (2010) used in the analysis. In order to consider the influence of material properties, the dimensions of the two braces are the same as experimental data of the hot-rolled brace in this study.

Table 3. Dimensions and Material properties

Specimen	D/t	λ	D (mm)	t (mm)	L (mm)	A (mm²)	tensile coupon test		Young's modulus (N/mm²)
							σ_y (N/mm²)	σ_u (N/mm²)	
Cold-formed	13.46	62.94	168.3	12.5	5050	6118	451	506	200000
Hot-rolled							368	500	

Material properties in Table 3 are used for determining parameter for Chaboche model showing in Table 4.

Table 4. Parameter for Chaboche model

Specimen	R (N/mm²)	C_1 (N/mm²)	γ_1	C_2 (N/mm²)	γ_2
Cold-formed	402	11220	107.9	860.2	23.5
Hot-rolled	368	5435	41.17	797.5	6.8

Load pattern is incremental displacement load which repeats compression and tension by Packer (2010). Since both specimens are the same length, both specimens give the same displacement.

The FEM results with Chaboche model for cold-formed brace (Specimen; CHS-C) and hot-rolled brace (CHS-H) exhibited the hysteretic relations shown in Figure 5. In the FEA results of CHS-C, cumulative damage at mid-length led to local buckling on the 27th cycle as shown in Figure 6 (a). The FEA results of CHS-H finished the entire loading protocol without developing a typical local buckling shape and instead formed an extensive yield region around the brace mid-length with no stress concentration at the member during compression cycles showing in Figure 6 (b).

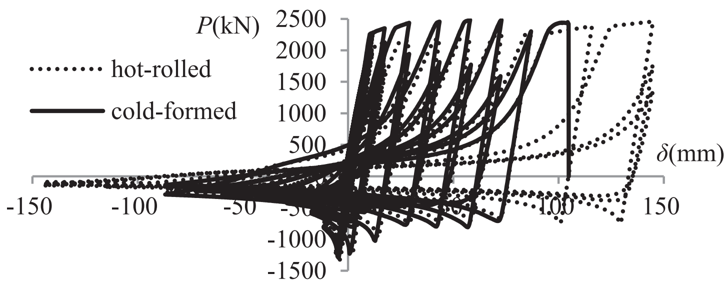
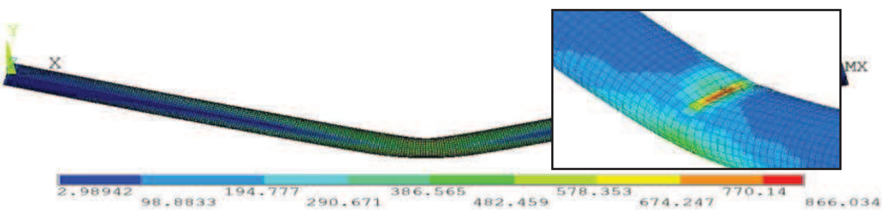
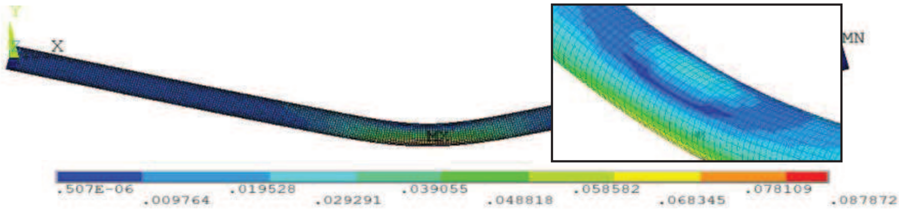


Figure 5. P-δ Curve



(a) Cold-formed



(b) Hot-rolled

Figure 6. Deformation of braces

4 Conclusion

FEA using the cyclic constitutive model with nonlinear kinematic hardening were carried out to simulate the cyclic behaviors of the brace tests using the material parameters calibrated by the monotonic coupon test results.

The constitutive model can simulate the cyclic behavior of the brace with the influence of the slenderness ratio, the diameter to thickness ratio and the material properties changing by the manufacturing process of cold-formed and hot-rolled.

The FEM results with Chaboche model used solid-shell element showed a significant difference in the shape of local buckling for cold-formed brace and hot-rolled brace.

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