ANALYTICAL AND EXPERIMENTAL STUDY ON STEEL BRACES WITH STRONGER MIDDLE LENGTH TREATED BY INDUCTION HARDENING

K.A. Skalomenos¹, M. Kurata², Y. Fukutomi³ and M. Nishiyama⁴

ABSTRACT

This paper presents an analytical and experimental investigation on the seismic behavior of steel braces with stronger mid-length manufactured by using the induction hardening process. Induction heating (IH) technology directly heats the brace middle, and then by quenching the heated portion in water the brace middle reaches a higher strength. The concept of designing steel braces with a stronger middle portion aims to improve buckling behavior by increasing buckling load and reducing the abrupt change in compressive strength during the post-buckling path. Based on the analysis results, the IH-treated brace exhibits an increase of the buckling load and a significant improvement of the post-buckling behavior for intermediate values of slenderness ratio. Moreover, as the length of IH portion increases the negative slope of post-buckling region becomes less steep, moderating the deterioration of the compression strength. Based on test results, the proposed brace exhibited an increase of the buckling load nearly by 16% and a higher tensile post-yielding stiffness equal to 6% of the initial stiffness. An earlier than expected global instability was observed.

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Introduction

Concentrically steel braced frames (CBFs) constitute the main seismic-resistant mechanism in steel structures (Fig. 1a). The most frequently used steel braces in CBFs, referred herein as conventional buckling braces (CBB), provide with an increased strength and stiffness for the control of lateral drifts in frames and absorb seismic energy through yielding of the braces [1,2]. However, they suddenly lose compressive strength when they buckle (Fig. 1b) [2-4]. Severe local deformations occur in the middle followed by fracture in a tension load (Fig. 1c). The treatment of this weakness can be the basis for developing alternative design scenarios for steel braces [5-9].

The present paper evaluates the cyclic behavior of steel braces treated by induction hardening. A part of brace length is heated by induction heating (IH) technology [10] and then

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quenched. IH is a very efficient non-contact way to heat up only a selected area of steel members over 1000 °C, and then, by cooling the steel in water immediately (quenching) the workpiece obtains certain material properties, such as two-to-three times increased strength. Due to the recent progress in manufacturing (by Netsuren Corporation in Japan), it is now possible to prepare IH-treated large size steel members. This study proposes for steel braces an IH-treated circular hollow tube, where a specified length in the middle of the tube has much higher strength than the rest tube which remains the properties of the conventional steel. The concept of designing steel braces with a stronger middle portion aims at achieving a controlled post-buckling behavior. The middle IH-part remains elastic and tends to prevent the brace from severe overall buckling behavior, while the conventional part yields and absorbs the seismic energy through inelastic deformations. In tension, the brace exhibits an increased post-yielding stiffness due to the higher levels of strain hardening achieved in yielded portion. High post-yielding stiffness can be advantageous to the overall building response as it can reduce residual displacements [11].

The present paper presents analytical and experimental results on the seismic performance of the proposed IH-treated brace. A parametric study was conducted using the OpenSees software [12] to examine the influence of several design parameters, such as, the slenderness ratio $\lambda$, the yield stress of IH steel, and the ratio of the length of IH part to entire brace length. Then, results from the experimental study are presented. The study evaluates the cyclic behavior of two circular hollow section braces; one following the conventional brace design and the other using the proposed concept. The tests were conducted quasi-statically imposing a typical cyclic loading protocol. Gusset plate connections designed to behave like pins were used to connect the bracing members to the loading frame.

**Steel brace with stronger middle length: concept**

Fig. 2a and b illustrate the design concept of the proposed IH-treated brace. The main characteristic of the proposed brace is that the middle portion has several times higher strength than the rest brace (unheated portions near brace ends) which maintains the yield stress of conventional steel. This design concept promotes strain concentration on the unheated portions, while the middle part
remains elastic. The critical section shifts from the mid-length near to the brace ends (Fig. 2b). The brace member can reach the conventional yield stress, $\sigma_y$, before buckling occurs and therefore the compression load increases. Then, by increasing axial deformation the brace buckles due to the plastification of unheated portions, but for a given axial deformation the transverse deflection decreases, and post-buckling behavior becomes more stable. IH-treated steel appears to have similar material properties with those of ultra-high strength steels [13].

**Buckling mode**

The buckling mode that governs the brace response depends on the location of the plastic hinge. In general, this location can be either at the mid-length or somewhere within the unheated portion. The final location depends on the capacity of the middle portion to resist the second order moment caused by the initial imperfections. Assuming that a sinusoidal curve describes better initial imperfections which increase elastically with axial force (Fig. 2c), the stress at a location $x$ of brace length can be obtained from,

$$\sigma(x, N) = \frac{M(x)}{Z} + \frac{N}{A} = \frac{N}{1 - N/N_E} \frac{\alpha_0 \sin \left( \frac{\pi x}{l} \right)}{Z} + \frac{N}{A}$$

where, $l$ is the entire length of steel brace; $A$ is the cross-sectional area; $Z$ is the section modulus; $\alpha_0$ is the initial imperfection; $N$ is the axial force; $M(x)$ is the bending moment; and $N_E$ is the elastic buckling load. The location of plastic hinge can be determined by comparing the maximum stress of the unheated portion, $\sigma_b$, and middle portion, $\sigma_m$, with the yield stress of each portion. In the proposed IH-treated steel brace plastic hinge is expected to be formed in the unheated portion, when $\sigma_b > \sigma_{CS}$ and $\sigma_m < \sigma_{IH}$, which results in an un-symmetrical buckling mode, as shown in Fig. 3a. In conventional steel braces, where all of the brace is unheated, plastic hinge forms in the mid-length as $\sigma_m > \sigma_{CS}$ resulting in a middle-kinked member (common buckling mode).

**Post-buckling behavior**

Fig. 3a depicts a pin-supported brace with two-flange cross-section (web excluded) as a simple
example to examine the post-buckling behavior. The brace consists of two rigid (in term of bending) portions and a region that can be plastified at the unheated portion. This model is identical to the model used to explicate Shanley’s theory [14]. In the buckled condition shown in Fig. 3a, the lateral deflection at the location of plastic hinge, \( u \), and the end rotations, \( \theta_1 \) and \( \theta_2 \), are related to \( u = \alpha(1-\alpha)(\theta_1 + \theta_2)l \); \( \alpha \) is the ratio of conventional part length to entire length. The axial displacement, \( w \), is given as the sum of the elastic deformation (due to the axial force), \( w_e \), the deformation provided by lateral deformation, \( w_b \), and plastic deformation in the hinge region, \( w_p \),

\[
w_e = \frac{NL}{EA}, \quad w_b = \frac{l}{2}\alpha(1-\alpha)(\theta_1 + \theta_2)^2, \quad w_p = d \frac{\theta_1 + \theta_2}{2}
\]

(2)

where \( d \) is the depth of the cross-section. The equilibrium of moment at the hinge location is,

\[
M = Nu = N\cdot \alpha(1-\alpha)(\theta_1 + \theta_2)l
\]

(3)

For elastoplastic stress – strain relationship, the following yield condition satisfies \( M - N \) interaction: \( M/M_p + N/N_y = 1 \); \( M_p \) is the full-plastic moment and \( N_y \) the yield axial force. For the two-flange section, \( M_p \) can be defined as,

\[
M_p = \frac{A}{2} d\sigma_y = \frac{d}{2} N_y
\]

(4)

where \( A \) is the cross-section area. In view of the above equations, the hinge rotation is equal,

\[
\theta_1 + \theta_2 = \frac{1}{2\alpha(1-\alpha)} \frac{d}{l} \left( \frac{N_y}{N} - 1 \right)
\]

(5)

Using Eq. 5 and Eq. 2, axial force – axial deformation relationship can be defined as follows,

\[
\frac{w}{k_e} = \frac{w_e + w_b + w_p}{k_e} = \frac{N}{N_y} + \frac{1}{4\alpha(1-\alpha)} \frac{2}{\pi^2\lambda_c^2} \left[ \frac{N_y}{N} \right]^{-2} \left( \frac{N_y}{N} \right) - 1
\]

(6)

Figure 3. (a) Load and geometry conditions of rigid brace with hinge; and (b) Definition of ultimate story drift (USD).
where \( \varepsilon_y \) is the yield strain; \( \lambda_c \) is the normalized slenderness ratio equal to \( (N_y/N_E)^{0.5} \). For a given axial load \( N \), Eq. 6 reveals that when \( \alpha \) equals 0.5, axial deformation takes the smallest value. When \( 0 < \alpha < 0.5 \) or \( 0.5 < \alpha < 1 \) larger axial deformation corresponds to same \( N \) which indicates that negative slope in the post-buckling region becomes more gradual and strength deterioration decreases.

**Parametric Study**

This section presents a parametric study on the compression behavior of the IH-treated brace conducted using the OpenSees software [12]. The parametric study concerns the following parameters: a) the slenderness ratio \( \lambda \); b) the yield stress of IH steel; c) and the ratio of IH length to entire brace length.

**Opensees analytical model**

A compact circular hollow steel section (HSS) with diameter (\( D \))-to-thickness (\( t_b \)) ratio of 32.7 is adopted for the braces. The \( D \) equals 114 mm and \( t_b \) 3.5 mm. The model was divided into 8 elements along the cross section and 30 elements along the length. The material Steel02 was assigned in each fiber with 328.60 MPa yield stress [5]. To simulate the buckling behavior, a sinusoidal curve and an imperfection in the middle of the brace equal to \( l/500 \) were assumed. Boundary condition in the brace ends were pins and the incremental axial displacement was applied to one brace end. To evaluate the strength deterioration after buckling, an index namely “ultimate storey drift (USD)” was defined. USD index is the storey drift at which compression strength is equal to 80% of buckling load, as shown in Fig. 3b.

**Slenderness ratio**

The slenderness ratio \( \lambda \) strongly affects the behavior of brace in compression. In this analysis, normalized slenderness ratio varies from 0.26 to 1.6 for the length of brace member from 800 mm to 5,000 mm with the same cross-section. The yield stress of IH steel was assumed to be four times higher than that of conventional steel and the length of IH portion 60% of the entire length of the member. Analysis results are shown in Fig. 4a and Fig. 4b. Fig. 4a compares the buckling curves of conventional buckling brace (CBB) with that of IH-treated brace (IH-CBB) for the examined

Figure 4. Analysis results of parametric study: (a) buckling curves for conventional and IH steel brace; and (b) post-buckling behavior in terms of USD index.
range of normalized $\lambda$. The buckling load in Fig. 4a was normalized by $N_y$. Fig. 4b shows the USD index versus the normalized $\lambda$. From these figures, an increase of buckling load and a significant improvement of the post-buckling behavior is observed for intermediate $\lambda$ in IH-CBB.

**Yield stress of heated part**

Fig. 5a shows analyses results related to the influence of the yield stress ratio between IH steel and conventional steel (CS), $\sigma_{IH}/\sigma_{CS}$. For this set of analysis, the brace member had length equal to 2,000 mm (normalized slenderness ratio 0.72). The figure indicates that there is no influence of IH steel on the buckling load for values of the ratio $\sigma_{IH}/\sigma_{CS}$ more than two. Same observation applies to the USD index. This is because a ratio of two is sufficient to keep the IH part elastic until large axial deformations. Note that the observation above is valid for $\lambda$ around 0.7.

**Length of IH portion**

Fig. 5b shows analysis results related to the influence of the length of IH portion. The yield stress of IH steel was assumed to be four times higher than that of conventional steel for conservatism. The length of IH portion was express as ratio of IH length to the total length of brace member. Seven models with different ratio (80%, 73%, 67%, 60%, 53%, 46%, 0%) were analyzed. The analysis results suggest that as the ratio increases the USD index appreciably increases. However, very large ratio of IH portion significantly increases the strain demand within the unheated portion which may trigger premature fracture under tension.

**Experimental study**

**Test plan**

This section presents experimental results on two half-scale circular hollow section braces; one following the conventional brace design (CBB) and another using the proposed concept (IH-CBB). Fig. 6a illustrates the dimension details of the test specimens. Gusset plate connections designed following the recommendations of AISC (2010) [15,16] were used to connect the brace into the loading fame. The gusset plate had a clearance distance equal to two times its thickness ($2 \times 12 =$}

![Figure 5. Analysis results of parametric study: (a) influence of IH-to-CS yield stress ratio; and (b) influence of the length of IH portion.](image-url)
24 mm) to accommodate the inelastic rotations resulting from the out-of-plane inelastic deformations of braces. The cross-section of braces is the same as that used in the analytical study. Specimens had a clearance-to-clearance length of 2,131 mm and a normalized slenderness ratio = 0.70. The clear length of the steel tubes was 1,575 mm. In IH-CBB the ratio of IH portion was 60% of the entire length. Based on coupon test results, yield strength of IH portion was found to be 2.6 times larger than that of conventional one.

Fig. 6b shows the loading frame. The specimen was arranged in a four-pin frame at a 45° angle, such that only the brace resisted the applied force. A cyclic load was applied by imposing cyclically varying lateral displacements at the top of the frame with the aid of a hydraulic jack fixed to the steel reaction wall. The lateral loading history comprised several drift angle levels—0.1, 0.25, 0.5, 0.75, 1, 1.5, 2%—each imposed for two cycles.

**Test results**

Figs 7a and 7b depict the out-of-plane deformation (transverse deflection) of both CBB and IH-CBB, respectively, up to 1.0% compression story drift. The out-plane-deformation was measured...
by placing displacement transducers along the length of the brace. From these figures it can be easily observed the different buckling mode between the two brace specimens. In the CBB, the plastic hinge was formed in the mid-length, while in the IH-CBB in the unheated portion. The IH treatment successfully controlled the overall buckling behavior. In addition, the out-of-plane deformation in IHC-BB was smaller than that of CBB at 0.25% story drift, demonstrating the effectiveness of the proposed design to prevent buckling and increase the buckling load.

Fig. 8 shows hysteresis curve of the normalized (by yield strength) lateral load versus lateral storey drift. Table 2 provides with experimental values of important design quantities, such as the elastic stiffness, yield strength in tension and buckling load, and maximum tensile strength. Drift levels at which, overall buckling, local buckling and fracture occurred are also provided. In Table 2, the value within brackets is the measured drift angle (positive for tension and negative for compression). The yield strength is based on strain gauge measurements.

Compared to the CBB, the IH-CBB exhibited an increase in the buckling load nearly by 16%. Higher post-yielding stiffness in tension was also achieved equal to 6% of the initial stiffness. IH-CBB buckled earlier than expected based on the preliminary OpenSees analysis, perhaps because of the large out-of-plane imperfections imposed by the loading frame (four-pinned frame shown in Fig. 6b). Then, local buckling occurred within the unheated portions, as shown in Fig. 8c. This local deformation occurred suddenly and lateral jack could not maintain the feedback displacement. The lateral displacement which finally applied to the brace was larger (story drift =

<table>
<thead>
<tr>
<th>Spec.</th>
<th>Elastic stiffness (kN/mm)</th>
<th>Yield strength (kN)</th>
<th>Buckling load (kN)</th>
<th>Maximum strength (kN)</th>
<th>Global buckling (cycle)</th>
<th>Local buckling (cycle)</th>
<th>Fracture (cycle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBB</td>
<td>62.3</td>
<td>225 [0.25%]</td>
<td>-221 [-0.14%]</td>
<td>304 [2.07%]</td>
<td>1st -0.5 %</td>
<td>2nd -1.0 %</td>
<td>2nd 2.0 %</td>
</tr>
<tr>
<td>IH-CBB</td>
<td>61.8</td>
<td>206 [0.225%]</td>
<td>-256 [-0.25%]</td>
<td>315 [1.01%]</td>
<td>1st -0.5 %</td>
<td>1st -0.5 %</td>
<td>2nd 1.0 %</td>
</tr>
</tbody>
</table>
1.2%) than the targeted one (story drift = 0.5%) inserting rapidly the brace member into high inelastic deformation levels. The large strain concentration promoted a severe local buckling failure followed by global out-of-plane instability. The positive influence of IH portion on post-buckling behavior was not recorded in the test. Further study requires numerical simulations considering local buckling effect and reconsideration of the effective range of IH treatment in terms of normalized slenderness ratio and width-to-thickness ratio.

Conclusion

This paper presents analytical and experimental investigation on steel braces with stronger mid-length portion manufactured by using the induction hardening process. The concept of designing steel braces with a stronger middle portion aims to improve buckling behavior by increasing the buckling load and reducing the abrupt change in compressive strength during the post-buckling path. An increased post-yielding stiffness in tension can also be achieved which improves seismic performance of braced frames. Based on the present study, main conclusions are as follows,

Analytical study
- The proposed IH-treated steel brace with intermediate values of slenderness ratio exhibited an increase of the buckling load and a significant improvement of the post-buckling behavior.
- The improvement was capped at the values of IH-to-conventional yield stress ratio more than two.
- As the length of IH portion increased the negative slope in post-buckling region became less steep, moderating the deterioration of compression strength.

Experimental study
- In the IH-treated steel brace under consideration, the 2.6 times increase of mid-length strength increased the buckling load nearly by 16% due to the prevention of overall buckling. A higher post-yielding stiffness around 6% of the initial stiffness was also achieved.
- A severe local buckling occurred within the unheated portions which led to an earlier global instability than excepted.

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