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Use of induction-heating in steel structures: Material properties and novel brace design

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ABSTRACT

Induction heat (IH) treatment technology is a very efficient way to increase several times the strength of a selected part of steel elements. This paper presents an experimental investigation on the material properties of IH-treated steel elements and a novel application to steel braces. The IH treatment technology and manufacturing process are first reviewed and then, the new material properties obtained by a series of coupon tests and Vickers hardness tests are reported. Compared with the conventional steel, the IH-treated steel offers two-to-three times higher yield stress and tensile strength, but three times lower fracture ductility. The proposed steel brace is a steel tube with a partial strength enhancement in its cross-section. One-half of the section is treated by IH, while the remaining maintains the properties of conventional steel. The conventional steel part yields earlier and dissipates energy, whereas the IH steel part remains elastic until large deformation. An intentional eccentricity is also introduced along the brace length to magnify further the contrast of material benefits. The effective combination of the partial strength enhancement and eccentricity provides the brace with a beneficial multiphase response. The brace exhibits a high tensile post-yielding stiffness nearly equal to 20% of the initial stiffness and stably dissipates energy during cyclic loading up to 2.0% story drift by delaying the onset of local buckling.

1. Introduction

In the last decades, a number of experimental and analytical studies has been carried out on the inelastic seismic responses of steel bracing members [1–7]. Steel bracing members constitute the main seismic-resistant mechanism in steel braced frame structures. The seismic design of concentrically braced steel frames (CBFs) requires high strength and stiffness to meet serviceability requirements during frequent earthquakes, and a ductile behavior to prevent the collapse in strong earthquakes [8–10]. The information obtained from the previous research programs and the experience gained from past earthquakes have revealed some drawbacks in the seismic behavior of steel braces. Steel braces provide limited post-yielding stiffness to structures that may result in a sudden increase of floor deformation and a soft-story failure mechanism at large deformation [11,12]. Although steel braces efficiently absorb seismic energy through yielding, they lose rapidly compressive strength when they buckle. Overall buckling is followed by a local buckling at mid-length of the brace, which promotes early fracture limiting structural ductility. Moreover, steel braces are unable to simultaneously satisfy performance objectives in terms of force and deformation. It is critical, therefore, to mitigate seismic damages derived from the inelastic behavior of braces and improve their design adjustability. The treatment of the negative traits of steel braces can be the basis for developing high-performance braces [13–22] that can comply more sufficiently with the performance objectives of modern seismic design methodologies [23–25].

This study suggests a novel design of steel braces that provides an appreciably large post-yielding stiffness and large inelastic capacity by delaying the onset of local buckling. The induction heat (IH) treatment technology, also called as induction hardening process, is applied to brace design and manufacturing. The IH-treatment technology combines induction heating and quenching, and is a very efficient way to increase the hardness and strength of steel. In mechanical engineering and aerospace engineering, induction is used mostly to harden engine components, such as gears, drive shafts, torsion bars, springs, rocker arms, valves, etc. or rock drills, stampings, and spindles. In such applications, individual steel workpieces are hardened separately to ensure its own precise specifications. In civil engineering, post-tensioning bars are a well-known product of induction heating. So far, the applications have been limited to slender or short steel elements. Due to the recent progress in manufacturing, it is now possible to apply IH-treatment technology to full-scale structural steel members, such as wide-flanges and hollow structural sections (HSS) with a precise control, [manufacturing capability by Neturen Corporation (http://www.k-neturen.co.jp/

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0143-974X/

english/tabid/227/Default.aspx) – patent under application]. Development of highly-reliable and cost-effective IH-treated structural systems can make induction heating technology readily available to steel structure construction and design, and many new structural systems will be introduced. The proposed brace concept is the first application of the IH treatment technology to large-scale structural steel members.

First, the present paper introduces the proposed design concept for steel braces made of circular HSS, discussing in detail on its expected hysteresis behavior. Then, the manufacturing process and the new material properties obtained from the application of the IH-treatment to the circular HSS are introduced. Series of compression and tension coupon tests and Vickers hardness tests were conducted to gain a clear insight into the new material properties with respect to the yield stress, ultimate strength, ductility and fracture capacity. The influence of the heat-affected-zone (HAZ) to the material properties was also examined. Finally, an experimental study on the cyclic behavior of the proposed brace is presented and the performance of the proposed concept in comparison with the conventional brace design is discussed.

2. IH brace concept

The brace utilizes an IH-treated circular HSS, as shown in Fig. 1(a). One-half of the brace section has a two-to-three times higher strength than the other half which maintains the material properties of conventional steel. This significant strength variation in the cross-section is achieved by the IH-treatment technology. The IH-treated steel part has about 2.6 times higher yield stress than the conventional steel part. In the proposed concept, the conventional steel part yields when a relatively small axial force is applied. The conventional part of the brace yields earlier and dissipates the seismic energy, whereas the IH steel part remains elastic and is expected to act as a source of elasticity and restoring force beyond the yielding of the conventional steel part. The concept of designing steel braces with a distinct transition in strength has introduced in the past with the aim of achieving a multi-phase seismic response by combining discrete steel parts made of different steel grades [26].

The other design feature of the proposed brace is the intentional eccentricity which is introduced along the brace length, as shown in Fig. 1 (a) [21]. The distribution of strain demands in the cross-section of the brace becomes asymmetric due to the eccentrically applied axial force. The eccentricity magnifies the contrast of the material properties of the IH and conventional steel. The conventional steel part is subjected to larger strain demands and yields earlier, whereas the IH steel part behaves elastically until larger deformation since it is subjected to lower strain demands. The dual action of the partial strength enhancement and eccentricity realizes a unique hysteresis behavior of the developed brace, as shown in Fig. 1(b). Under tension, the brace exhibits a trilinear behavior providing with a high post-yielding stiffness. Structures with a high post-yielding stiffness in their story drift and shear relationship, tend to absorb a large quantity of energy, uniformly distributed over the stories [27,28], and sustains reduced strength and residual displacement demands [18,29–32]. In addition, systems with high post-yielding stiffness prevent the structures from the soft-story failure mechanism, which enable the structures to satisfy the requirements of a multi-hazard seismic design more rationally [21,33].

In compression, an almost bilinear behavior is observed. The brace transits into the post-buckling behavior smoothly without a severe drop of compression force as observed in conventional steel braces. Furthermore, due to the overall bending behavior and the existence of the IH steel part, which serves as an elastic spine, stresses and strains are distributed more uniformly along the brace length. Local deformation in the middle delays until high compression deformations. As a result, the fracture capacity of the member increases, offering an enhanced ductility. The increased ductility capacity in structures mitigates the collapse risk under maximum considered earthquakes and reduces strength demands at the preliminary stage of seismic design [34–36].

In the last part of the paper, experimental results of the cyclic behavior of the proposed IH steel brace are presented. The IH steel brace was subjected to a cyclic lateral load protocol with variable intensities of story drifts ranging from 0.10% to 3.0%. Its performance is compared with that of a corresponding steel brace designed with an intentional eccentricity only (no IH-treated section), named the brace with intentional eccentricity (BIE) [21], and a corresponding conventional steel brace (without eccentricity and IH-treated section), named the conventional buckling brace (CBB).

3. Induction heat treatment technology

Structural members constructed by combining discrete steel parts made of different steel grades are characterized by strength heterogeneity in their cross-section or along their length. Members composed of different material strength can minimize or concentrate their damage in predefined locations, and can exhibit an overall controlled behavior. In this context, the IH-treatment technology offers the appealing perspective to design such members with distinct variations in strength without the need to combine discrete steel parts made of different steel grades. In this study, IH is applied to a compact circular HSS with a diameter (D = 114.3 mm) and thickness (t_b = 3.5 mm), namely STK400 (made of steel material equivalent to A36 in the United States for hollow sections). The nominal carbon content in STK400 is smaller than or equal to 0.25%.

The IH-treatment technology uses the induction heating as a very efficient non-contact way to controllably heat up only a selected part of the steel member. As introduced in Fig. 1, only the one-half of the cross-section is treated. Fig. 2 shows the process of the IH treatment. The circular HSS is placed horizontally and simply supported at its

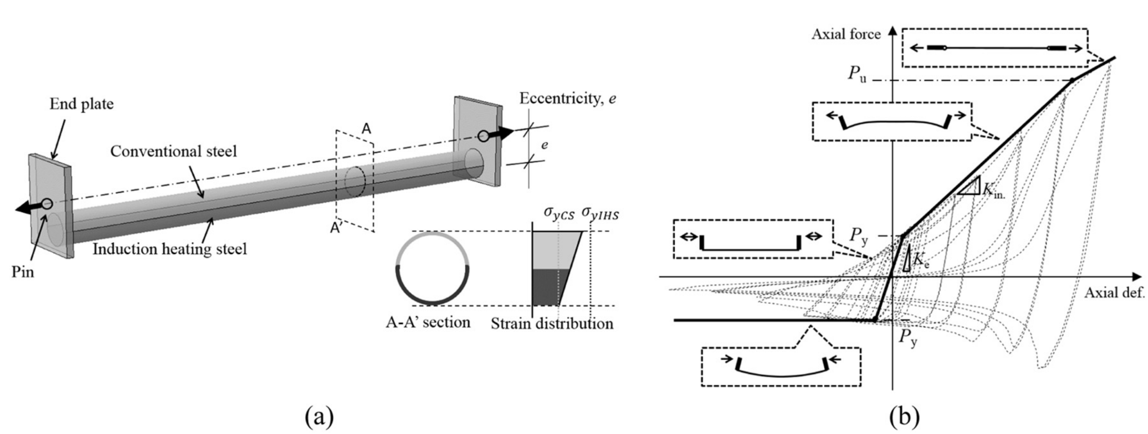

Fig. 1. Introduction of IH-brace: (a) Configuration; (b) Hysteretic behavior.