Journal of Constructional Steel Research 97 (2014) 114–126

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Charpy V-notch impact toughness of cold-formed rectangular hollow sections

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ARTICLE INFO

Article history:
Received 10 December 2013
Accepted 14 February 2014
Available online 13 March 2014

Keywords:
Charpy V-notch impact toughness
Rectangular hollow section
Hollow structural section
Cold-formed
Direct-formed
Continuous-formed
Heat treatment

ABSTRACT

The notch toughness of cold-formed rectangular hollow sections (RHS), at low temperatures or in dynamic loading applications, has been a concern in North America for some time. For the assessment of notch toughness of RHS, steel product standards normally require testing of Charpy V-notch (CVN) coupons taken longitudinally from one of the flat faces not containing the weld. This tends to lead to the most optimistic notch toughness result for the cross-section. Thus, serious consideration must be given to the notch toughness of the corner and weld seam regions when low temperature or dynamic loading is a design criterion. In this study, a total of 378 CVN coupons were tested and complete CVN toughness-temperature curves were generated for the flat face, corner and weld seam regions of six North American RHS, to study the effects of cold-forming, heat treatment, cross-sectional geometry and welding on the CVN toughness around the cross-section of RHS. In particular, the CVN toughness properties of RHS cold-formed by different methods (direct-forming versus continuous-forming) were directly compared for the first time.

1. Introduction

The selection of steel for toughness, as specified by international steel product standards and design specifications, normally requires Charpy V-notch (CVN) impact testing of the material. A required toughness is commonly expressed in terms of the test temperature (e.g. 20 °C) at which a minimum CVN impact energy value (e.g. 34 J/cm^2, which is 27 J for a standard full-sized CVN coupon) shall be achieved.

As detailed in ASTM A370 [1], a CVN impact test is a dynamic test in which a notched coupon is struck and broken by a single blow in a specially designed machine. The measured test value is the energy used to break the coupon at the testing temperature. Testing temperatures other than room temperature are often specified in product standards. For steel products, the CVN test most commonly uses a standard full-sized (10 × 10 × 55 mm) rectangular beam-type coupon with a machined notch of specified geometry (2 mm deep). By plotting the energy absorbed by the coupons as a function of the testing temperatures, as shown in Fig. 1 [2], an energy absorption versus temperature transition curve can be produced. At temperatures in the upper shelf, CVN coupons normally fracture in a ductile manner, absorbing relatively large amounts of energy. At temperatures in the lower shelf, CVN coupons normally fracture in a brittle manner, absorbing considerably less energy. Within the transition range, the fracture is generally a mixture of both ductile and brittle fractures. The approximate relationship between the CVN energy-temperature curve and the fracture behaviour of a steel component is also illustrated in Fig. 1 [2].

There are various methods for the determination of the transition temperature [1–4]. As shown in Fig. 1, in this study the ductile-to-brittle transition temperature (DBTT) is defined as the temperature corresponding to half of the upper-shelf energy value [4]. The 34 J/cm^2 temperature, commonly defined as the beginning of the lower-shelf region in international steel product standards, is defined as the nil-ductility temperature (NDT) in this study. Below the NDT, the material is considered to be brittle under impact loading [2].

The modern design of structures made of cold-formed hollow structural sections (HSS) and their welded joints is largely dependent on the redistribution of stress in the inelastic range. Thus, the selection of HSS for CVN toughness is critical if low temperature or dynamic loading is a design consideration. For RHS in particular, previous research [5] has shown that the CVN toughness around the cross-section is sometimes highly heterogeneous due to the uneven degree of cold-forming. Thus, it is necessary to further explore the effect of cold-forming. There are two common manufacturing methods internationally for cold-forming RHS: direct-forming and continuous-forming. The direct-forming process includes: (1) roll-forming a coil strip directly into an open section with the desired rectangular shape; and (2) joining the edges of the open section by welding to form a closed rectangular shape. The cold-working in this case is concentrated at the four corners. The continuous-forming process includes: (1) roll-forming a coil strip first into a circular open tube; (2) joining the edges of the open tube by

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http://dx.doi.org/10.1016/j.jcsr.2014.02.005
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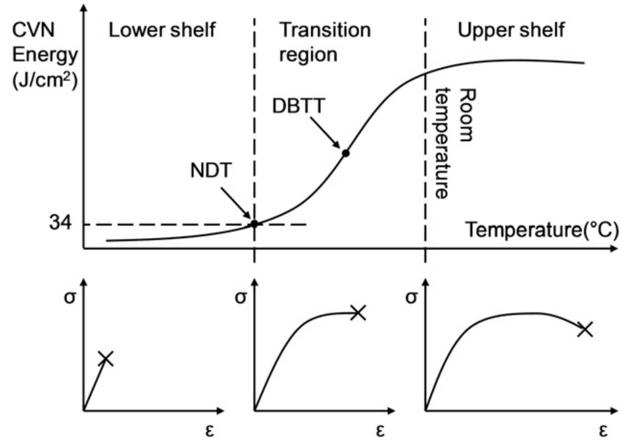

Fig. 1. Approximate relationship between the CVN energy–temperature curve and the fracture behaviour of a steel component [2].

welding to form a closed circular shape; and (3) flattening the circular tube walls to form the desired rectangular shape. In this latter case, the entire cross-section may contain high degrees of cold-working. It can be expected that there is a larger variation of CVN toughness between the flat face and the corner of direct-formed RHS than for continuous-formed RHS, as cold-forming reduces the CVN toughness of steel [2].

Failures of cold-formed RHS members due to cracking in the corners have been reported around the world. During the 1994 Northridge, California earthquake, there were incidents involving damage to RHS bracing members (including local buckling, tearing of steel at the corners and complete rupture of braces) due to cracking initiated from the corner as a result of low CVN toughness [6]. Thus, it is not certain that corner cracking can be arrested when it reaches the flat.

Thus, the use of cold-formed RHS for low temperature or dynamic applications is questionable if the selection of the member is based on the CVN toughness at the flat face only, as required by international standards. Hence, there is a need to incorporate the CVN toughness differences between the flat face and other locations around the RHS, for various member types and sizes, so that the selection of RHS can be based on better judgement. In this study, CVN tests were performed on coupons taken from various locations around the cross-sections of six RHS specimens with different production histories, to investigate the effects of different cold-forming methods and heat treatment.

2. Effects of chemical composition on material CVN impact toughness

The control of chemical composition is one of the methods to obtain the desired mechanical properties of structural steels. Product standards normally specify the ranges or limits of chemical elements which are considered necessary for the proper production of steel materials covered by the scope of the standards. For example, the chemical requirements for cold-formed HSS produced to ASTM A500 [7] are shown in Table 1.

Table 1
Chemical requirements in ASTM A500 [7].

Element	Composition, %			
	Grade A, B, and D		Grade C	
	Heat analysis	Product analysis	Heat analysis	Product analysis
Carbon, max	0.26	0.3	0.23	0.27
Manganese, max	1.35	1.4	1.35	1.4
Phosphorus, max	0.035	0.045	0.035	0.045
Sulphur, max	0.035	0.045	0.035	0.045
Copper, min	0.2	0.18	0.2	0.18

Low-carbon structural steels, commonly referred to as mild steels, normally have up to 0.25% carbon, 0.4%–0.7% manganese, 0.1%–0.5% silicon and some residuals of sulphur, phosphorus, and some other elements. They are not deliberately strengthened by alloying elements other than carbon and contain manganese for sulphur stabilization and silicon for deoxidation, thus their yield strengths cannot be increased beyond approximately 690 MPa without significant loss in toughness and ductility [3]. Although the effects of a single chemical element on the mechanical properties of steel are sometimes influenced by the effects of other elements, for simplification, the common elements and their effects on the CVN toughness of steel are usually discussed individually. The CVN impact energy–temperature curves for carbon steels of varying carbon content, and 0.30% carbon steels of varying manganese content are shown in Figs. 2 and 3 [3]. As can be seen in Fig. 2, for the steels investigated, the increasing carbon content (from 0.11% to 0.80%) increases the transition temperatures (from −46 °C to 150 °C) and decreases the upper-shelf energy (from 204 J to 33 J) primarily as a result of the increased strength. Despite the importance of strength, CVN toughness must also be considered when selecting a structural steel, thus a compromise has to be made sometimes. Manganese is the principal strengthening element in carbon structural steels. As can be seen in Fig. 3, for the steels investigated, the increasing manganese content (from 0.30% to 1.55%) decreases the transition temperatures (from 36 °C to −23 °C) while its effect on the upper-shelf energy is less obvious (increased from 128 J to 141 J). For applications involving exposure to low temperatures ranging from 0 °C to −200 °C, low-carbon and high-nickel steels are typically used. The effect of nickel content is to reduce the ductile-to-brittle transition temperature, therefore improving the toughness of the steel material at low temperature. Phosphorous is considered an impurity but sometimes is added for atmospheric corrosion resistance. It increases the strength and hardness of steel but significantly decreases its ductility and toughness. Silicon is primarily a deoxidizing agent and it tends to reduce steel ductility. Sulphur is considered an impurity which significantly reduces the fracture toughness of steels. It is necessary to keep sulphur content low, which is usually done by adding manganese to form manganese sulphides. However, the MnS inclusion may increase the susceptibility of the steel to lamellar tearing [3]. Investigations on the effects of these chemical elements on the CVN toughness of various steels have been brought together in ASM Handbook Vol. 1 [3].

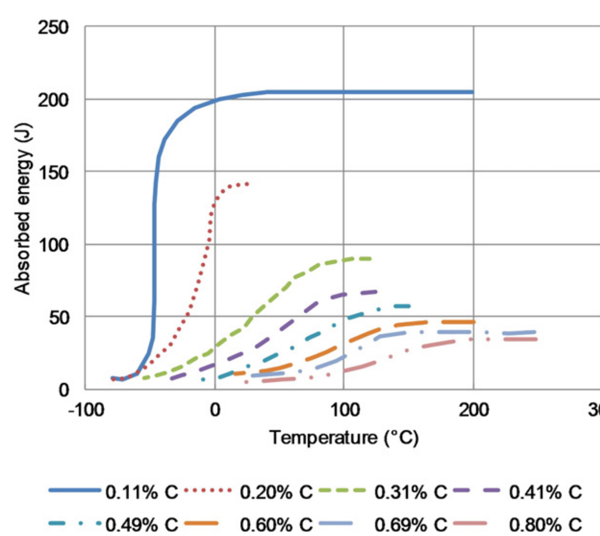

Fig. 2. Variation in CVN impact energy with temperature for carbon steels of varying carbon content [3].