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Short Communication

Residual ultimate strength of open box girders with cracked damage

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ABSTRACT

In this paper, the ultimate strength of open box girders with crack damage subjected to pure torque, compressive force, bending moment and combined loads is investigated using a commercial FEA program, ABAQUS. The ultimate strength reduction characteristics of the box girders due to cracking damage as a function of crack types, crack sizes and crack locations are studied. Based on the numerical results obtained from the present study, a simple model for predicting the residual ultimate strength of open box girders with crack damage under single load and combined loads is proposed. The suggested model has a simple form yet well represents the lower bounds of the reduced ultimate strength due to crack damage.

1. Introduction

As the design criteria has changed from the allowable stress design to the limit state design, we now focus on the ultimate capacity of structures (Alinia et al., 2011). Many experimental and theoretical investigations have been carried out to study the actual post buckling behavior and ultimate capacity of steel structures.

In order to predict the ultimate strength of damaged structures, the use of closed form expressions will be simple and efficient to use during the design stage. In this paper, a simple model to predict the residual ultimate strength of cracked box girders under torsion, compression and bending loads, where the damage due to cracking is treated as a main parameter, is developed.

Alinia et al. (2007) investigated the influence of central cracks on the residual strength of shear panels using FEA and proved that the length and angle of cracks may change the buckling behavior of shear panels, and certain combination of the length and angle of cracks can result in substantial degradation in ultimate strength. Paik et al. (2005, 2008 and 2009) experimentally and numerically investigated the behavior and ultimate strength of plates with transverse and longitudinal cracks under axial compression or tension.

Ungureanu (2010) analyzed the failure mechanism of thin-walled cold-formed steel structures in compression and bending. The conclusions were drawn that short members failed by forming local plastic mechanisms and slender members, due to the interaction between local and overall buckling modes, collapsed by forming local plastic mechanism failure mode. The yield lime mechanism was used to predict the post-collapse behavior and to evaluate the load-carrying capacity.

Alinia et al. (2009) clarified how, when and why plastic hinges of shear failure mechanism actually form and observed that shear-induced plastic hinges only develop in the end panels. Later Alinia et al. (2011) extended to clarify how, when, why and where plastic hinge form in flanges and found that although the principal compressive stresses in the center of the web plates remained constant after an elastic buckling, they did increase considerably in other regions.

The strength interaction equations for combined loadings are well presented by several researchers. Pi and Bradford (2001) investigated the nonlinear elastic-plastic behavior of steel I-section beams subjected to combined bending and torsion actions and proposed simple formulas for their design. Graciano and Casanova (2005) investigated the ultimate strength of I-girder webs subjected to the combined action of patch loading and bending moment. Kim and Yoo (2008) analyzed the ultimate strength of rectangular steel box girders under the interaction of bending–torsion and bending–shear-torsion conditions and proposed simple equations to predict the ultimate strength. Paik (2009a and 2009b) studied steel stiffened-plate structures subjected to combined biaxial compression and pressure actions.

Based on inelastic theories, the following circular interaction equation was suggested by several researchers (Boulton and Boonsukha 1959; Jackson 1966; Yoo and Heins 1972) for the

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design of beams:

$$\left(\frac{M}{M_p}\right)^2+\left(\frac{T}{T_p}\right)^2 \le 1 \tag{1}$$

where M_p is the major axis full plastic moment of the cross section; and T_p is the full plastic torque of the cross section; M and T are the applied bending and torsion moment, respectively.

In this paper, an open box girder with varying crack types, crack sizes and locations is considered. The aim of the present study is to obtain insights into the ultimate strength behavior of cracked box girders under single load and combined loads. It is to be noted that the fracture related critical crack length considerations have not been included in the present study. Based on the numerical results obtained, a simple design formula for reduced ultimate strength of cracked boxes is proposed.

2. Finite element modeling

In this paper, three types of cracks in the girders were analyzed. Fig. 1 shows the location and size of cracks. The cracks were presumed to be through thickness, having no friction between their edges and no propagation was allowed. Simple supported boundary conditions were assumed throughout this research. At the torsional center of one end of the box was constrained as $u_x=u_y=u_z=0$ and the other was constrained as $u_y=u_z=0$. The external loads, such as torque, axial compressive force and bending moment, were separately applied on the torsional centers at the girder's end.

For the present series of analyses, the box length and width were fixed at $a=b=800$ mm. The opening was fixed at 800×672. The breadth of the opening was about 84% of the whole girder's breadth. The girder thickness was varied as $t=10$ mm, 15 mm and 20 mm. The elastic modulus of material was $E=205.8$ GPa and Poisson's ratio was $\nu=0.3$. The material was considered to behave in an elastic-perfectly plastic manner with yield stress $\sigma_Y=352.8$ MPa. The crack type, location and size were defined as shown in Fig. 1.

The Riks algorithm in the ABAQUS was chosen to carry out elastic-plastic large deflection analysis. The shell element S4R was used for modeling steel plates.Fig. 2 shows an example meshing of the crack box with a refined meshing around the crack and very dense meshing near the crack tips.

For box girders under various loading conditions, multiple buckling modes with $m-1$, m, $m+1$ half-wavelength might interact with each other characterized by an unstable post-buckling behavior. So it was very important to make certain of the localization of buckling patterns, that is to say, there was initial geometrical imperfection. It was assumed that the initial deflection shape of the box was equivalent to the buckling mode shape as shown in Fig. 3. The initial average deflection was assumed as:

$$\omega_0=0.1\beta^2 t \tag{2}$$

where the slenderness ratio: $\beta=(b/t)(\sigma_Y/E)^{1/2}$.

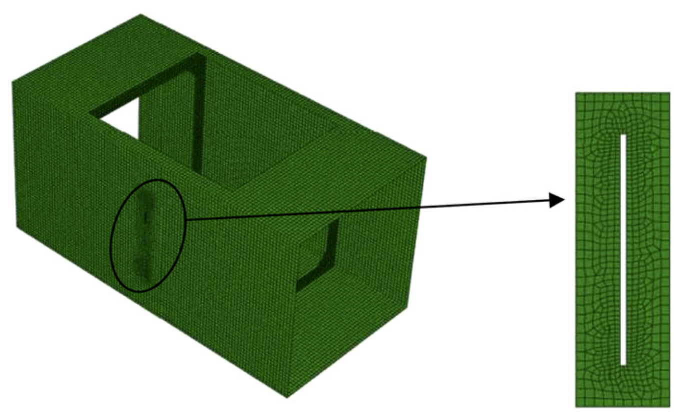

Fig. 2. A sample finite element meshing of a center-cracked box and local mesh refinement.

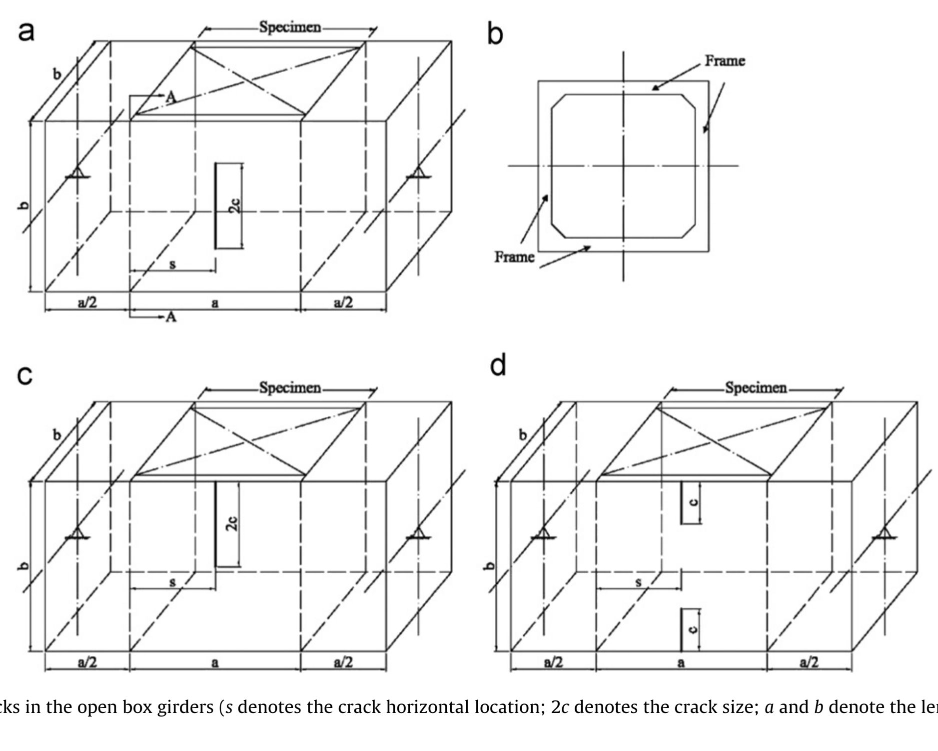

Fig. 1. . Three types of cracks in the open box girders (s denotes the crack horizontal location; $2c$ denotes the crack size; a and b denote the length and width of the girder separately).