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The collapse mechanism of corrugated cross section beams subjected to three-point bending

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ABSTRACT

In this paper, the collapse behavior of corrugated cross section beams subjected to three-point bending is studied by using the finite element method (FEM). In order to estimate the energy absorption characteristics of the beam, it is essential to estimate the relation between load and deflection in the process of the beam collapse after the peak load. It is found that in the collapse process of the beam the load is decreased by flattening of the cross section of the beam, and that the flattened shape can be quantitatively expressed in terms of the curvature radius of the plane of the top and bottom of the cross section. Based on the energy balance that external work is equated to the flattening deformation energy of the cross section, a new method is proposed for predicting the relation between load and deflection. The validity of the presented method is verified through a comparison with numerical results of FEM analysis under various conditions.

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1. Introduction

Guardrails prevent injury to people and harm to vehicles in traffic accidents. The capacity of a guardrail to absorb collision energy depends strongly on the corrugated shape of the cross section. In the present study, we aim to investigate the collapse mechanism of a corrugated beam, such as a guardrail, under three-point bending. For the bending collapse of a thin-walled beam with an I-shaped, V-shaped or U-shaped open cross section [1–3], or with a circular or rectangular closed cross section [4–7], collapse mechanisms based on the buckling and plastic hinges have always been assumed in the analyses; however, the application of such techniques to a corrugated section is difficult. Therefore, a new simple collapse mechanism will be necessary to establish design formulas for the load–deflection curve. In this paper, the collapse behavior of a corrugated cross section beam in the three-point bending is analyzed through numerical simulation using the finite element method (FEM). After elucidating the collapse mechanism, we shall establish design formulas for the load–deflection curve and energy absorption performance of the corrugated beam.

2. Analyzed model of FEM

Simplifying the guardrail geometry specified by the Japan Road Association, we take a beam of thickness t and length L with a corrugated cross section as shown in Fig. 1. In accordance with the guardrail specifications, in this study, we assume $L=2000$ mm and wall thickness of $t=2.3$ mm, 3.2 mm, and 4.0 mm. The commercial FEM analysis package MSC. Marc is used to simulate the quasi-static deformation of the beam when a rigid pillar of diameter $D=20$ mm pushes the beam perpendicularly at a distance a from the left edge of the beam. The beam is simply supported at both ends as shown in Fig. 1. Here, we disregard the friction between the beam and the rigid pillar.

In modeling the materials, we consider only isotropic and homogeneous elastic-perfectly plastic material that conforms to the von Mises yielding criterion with Young's modulus E and yield stress σ_s; in this study, we assume SS400 steel, which is actually used to construct guardrails, with $E=206$ GPa, $\sigma_s=245$ MPa, and Poisson's ratio $\nu=0.3$.

In formulating the nonlinear behavior, the updated Lagrange method is used to consider large deformation, and the Newton–Raphson method is used in the modified calculation to satisfy the equilibrium equation. To ensure smooth deformation in the modeling, the model was discretized using quadrilateral, bilinear thick shell elements measuring 10×10 mm^2.

3. Mechanism of collapse deformation

Fig. 2 shows the relation between the deflection δ and the load P applied to the rigid pillar after the pillar touches the beam with thickness $t=4.0$ mm at the distance $a=L/2$ from the left edge of the beam. As the figure shows, the load first increases with the deflection δ and reaches a peak load P_{cr}. Then, as the deflection δ

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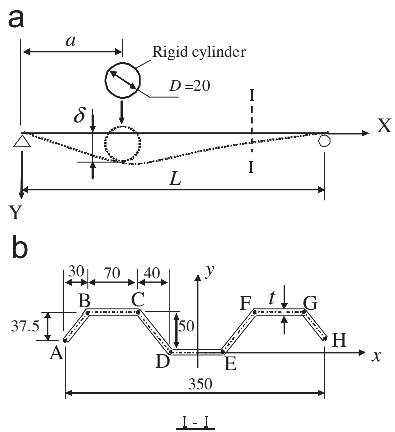

Fig. 1. Analyzed problem: (a) a rigid pillar pushes the beam at a distance of a; (b) cross section of the beam.

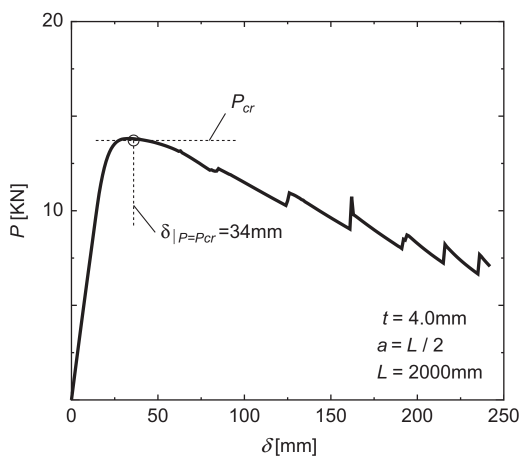

Fig. 2. Relation of P and δ obtained from FEM for a case of $a=L/2$ and $t=4.0$ mm.

further increases after reaching the peak load P_{cr}, the load decreases with collapse of the beam. The relation between load and deflection is important in calculating the energy absorption by the guardrail. As shown in Fig. 2, the relation between load and deflection after the peak load is important for calculating energy absorption because the deflection is small before the peak load. In order to predict the load–deflection curve after the peak load, an appropriate deformation mechanism of the beam after collapse is required. For thin-walled sections, the collapse mechanism based on plastic hinge formation, which is proposed by Kecman [4], has so far been adopted to predict the relation between load and deflection after bending collapse [5–7]. However, this mechanism cannot be applied to the present study, because a plastic hinge does not appear in the beam collapse process as shown in Fig. 3. As an example, Fig. 3 shows the deformation behavior of the beam model used in Fig. 2 and the contour map of the equivalent plastic strain. In the figure, the color becomes closer to white as the equivalent plastic strain becomes larger. Because of the symmetry, only half of the beam is shown in the figure; the circles indicate the points E, F and G at $X=L/2$, as shown in the cross section in Fig. 1(b). As the figure shows, the plastic zone (white area) spreads with deflection δ in the direction of beam length, and the deformation is global and no localized plastic hinges form. Such a deformation behavior in the bending collapse of the corrugated cross section beam cannot be explained by the collapse mechanism of Kecman [4], where a local buckling should occur and then plastic hinges should appear locally in the compressive region and the deformation proceeds with bending of the plastic hinges. Therefore, in the present study, a new

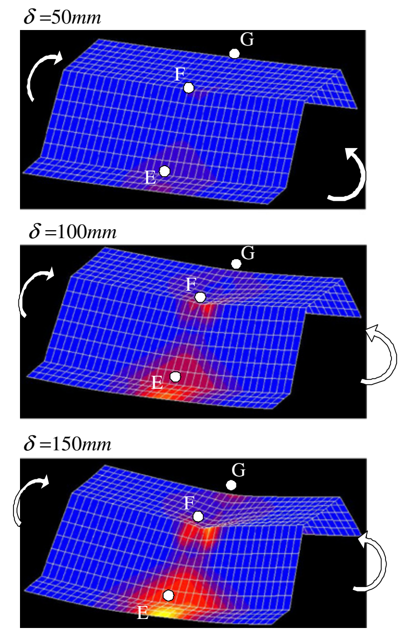

Fig. 3. Deformation of the beam used in Fig. 2 around $X=L/2$.

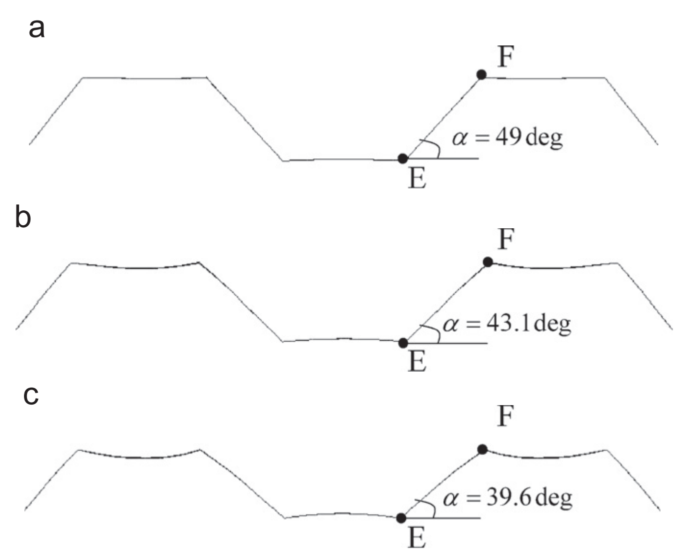

Fig. 4. Deformed cross section of the beam used in Fig. 2 at $X=L/2$. (a) $\delta=50$ mm, (b) $\delta=100$ mm and (c) $\delta=150$ mm.

simple method is proposed to predict the relation between load and deflection.

3.1. Flattening of cross section described by R_1

For the beam used in Figs. 2 and 4 presents the deformed cross section at $X=L/2$ for deflection of $\delta=50$ mm, 100 mm, and 150 mm. As shown by the variation of the angle α between the horizontal line and the plane EF in Fig. 4, the flattening of the cross section proceeds as a result of the increase in deflection δ. In other words, the decrease in the load after the peak load can be attributed to the flattening of the cross section of the beam.

Considering Fig. 4, we model the flattening as shown in Fig. 5(b): the angle β at the intersection remains unchanged; the slopes AB, CD, EF, and GH do not deform and simply rotate; the upper surfaces BC and FG and the lower surface DE exhibit bending deformation with an arc of radius R_1.

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