

Effect of Loading Rate Dependence on Unstable Behavior of Thin-Shell Structured Beams under Axial Compression- Elucidation of Mechanism and Effect of Beam Aspect Ratio on Loading Rate Dependence

Toshihiro Araki
Nissan Motor Company Ltd.

Yoji Shibutani
Osaka University Japan

ABSTRACT

The thin-shell structured beams that are used extensively in the vehicle body need to satisfy both strength requirements for crash safety and demands for weight reductions for environmental friendliness. This study focused on the loading rate dependence of reaction force, especially the maximum value, which is generated in thin-shell structured beams as a result of axial force inputs in a frontal crash. The mechanism generating the reaction force was made clear through a comparison with classical Euler buckling⁽¹⁾ and von Karman's effective width expression⁽²⁾. It was observed that a square cross section displays markedly large loading rate dependence, which can be approximated well by considering the effect of inertial force in the high loading rate region and by von Karman's effective width solution in the low loading rate region. Essentially, this dependence is governed by Euler buckling. When the length of two sides of a square cross section was fixed and the length of the other two sides was varied, it was found that von Karman's effective width solution approximated the overall reaction force reasonably well. Large variation in the aspect ratio of the beam, however, caused greater approximation error. That was shown to be influenced by the change in the order of Euler buckling caused by variation in the constrained state of each side at the corners of the beam.

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INTRODUCTION

The crash safety performance of vehicles has been dramatically improved through many innovations in strength design and improvements to occupant restraint systems. At the same time, there continue to be strong demands for vehicle weight reductions primarily for advancing environmental protection and energy conservation. In order to ensure safety and promote weight reductions, it is essential to have more precise structural design standards for the box-shaped thin-shell structured beams that are typically used as crash energy-absorbing structures on vehicles. It is easy to refer many papers regarding how to absorb energy efficiently^(3,4,5,6,7,8,9). And their unstable behavior in the axial direction has traditionally been analyzed by applying von Karman's effective width expression with respect to

elastic deformation. However, there are no reports in the literature of studies that have systematically investigated the loading rate dependence of the impact load (usually equal to a structure's maximum reaction force) near the elastic limit. In addition, the cross-sectional size and geometry of vehicle structural members generally vary in the longitudinal direction at the places where parts are suspended or joints are made with the cabin. At such places where cross sections vary, it is necessary to evaluate indexes showing which cross-sectional structures buckle first under a loading-rate-dependent impact load. Such evaluations provide valuable practical design guidelines.

The purpose of this study is to investigate the behavior of thin-shell structured beams from the following two perspectives.

(1). To investigate the loading rate dependence of the unstable behavior of square thin-shell structured beams using as the criterion the reaction force at the time the entire cross section yields uniformly. Comparisons are made with Euler's buckling solution and with von Karman's effective width expression that is an approximation of out-of-plane buckling of a flat plate based on experimental data. This is done to examine the mechanism causing unstable behavior in thin-shell structured beams in the low loading rate region that gradually approaches a quasi-static dynamic regime. In this paper, Euler buckling is used to describe the slight out-of-plane buckling that occurs initially in the deformation of the flat planes of thin-shell structured beams, albeit rectangular in shape.

(2). Out-of-plane buckling that occurs when the cross-sectional shape is changed from square to rectangular is investigated in the same way as in (1) above. The mechanisms causing different tendencies are investigated to obtain more universal design guidelines.

SIMULATION MODEL OF SQUARE THIN-SHELL STRUCTURED BEAM

The front side members positioned longitudinally in the engine compartment to suspend the engine, suspension and other parts are the principal energy-absorbing structures in a frontal crash. The object of the present analysis is a thin-shell structured beam that simulates front side members. As shown in Fig. 1, the simplified model represents a beam having a width and height $\alpha = 100$ mm, a length $\beta = 300$ mm and a plate thickness $h = 1.2$ mm. It is assumed that the beam is made of high tensile steel that has been used extensively in vehicles in recent years. The material has a Young's modulus of 206 GPa, Poisson's ratio of 0.3, yield stress of 833 MPa and a work hardening coefficient, approximated with the hardening rule of the n exponent, of $n = 0.07$ as its hardening property. Figure 2 shows the true stress versus the plastic strain curves of the material for two types of hardening. It is assumed that a load of 400 kN is generated when the entire cross section uniformly reaches its yield point. In order to make clear the factors underlying the simulation results, a perfect elasto-plastic model is also used that has an initial yield point of 833 MPa, as shown in Fig. 2. Loading is applied under displacement control in which an impactor applies displacement at a certain specified loading rate. The model takes into account contact between the impactor and the beam and between the beam and the fixed boundary face. Simulations were conducted using the PAM-CRASH general-purpose finite element code (Ver. 2009). Strain rate dependence was not considered in the model.

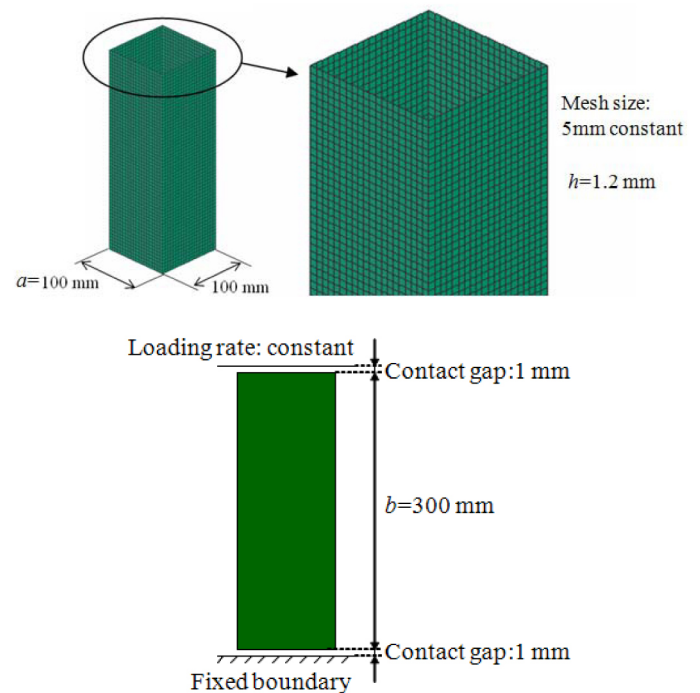


Figure 1. Specifications of FEM model of thin-shell structured beam.

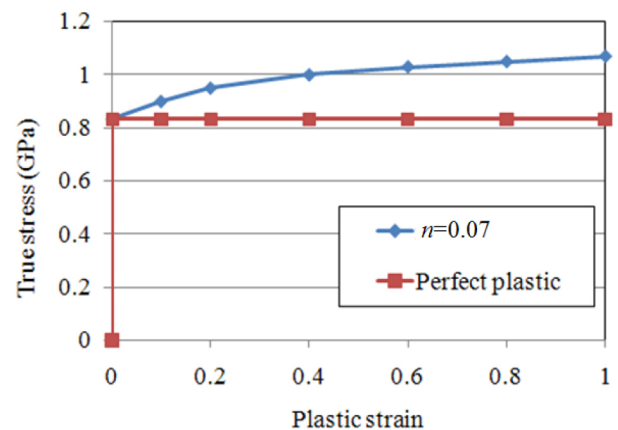


Figure 2. True stress versus plastic strain curves for two kinds of hardening.

LOADING RATE DEPENDENCE

Figure 3 shows the time history response of the reaction force generated in a thin-shell structured beam when axially crushed at a loading rate of 1 m/s (velocity of 3.6 km/h). The figure also shows the deformation modes and plastic strain distribution (in pink for 0.2% and higher) at the time of the initial condition ($t = 0$ ms), at the time the maximum load was generated ($t = 1$ ms) and at the time of complete crushing ($t = 10$ ms). In this example, after displaying maximum reaction force of 247 kN in the initial period, stiffness decreases to less than one-half of the maximum value as plastic

deformation progresses. As is clear from the deformation diagrams, only the local areas in contact with the impactor reach the yield point; the maximum reaction force obtained at that time is equal to only about 62% of the load (400 kN) at the time the entire cross section uniformly reaches its yield stress. Therefore, attention is focused here on the maximum reaction force generated in the region where slight plastic deformation begins to occur from a condition of uniform elastic deformation. This reaction force is an important dynamic quantity that determines the order for the onset of unstable deformation of parts and materials at the time of a crash.

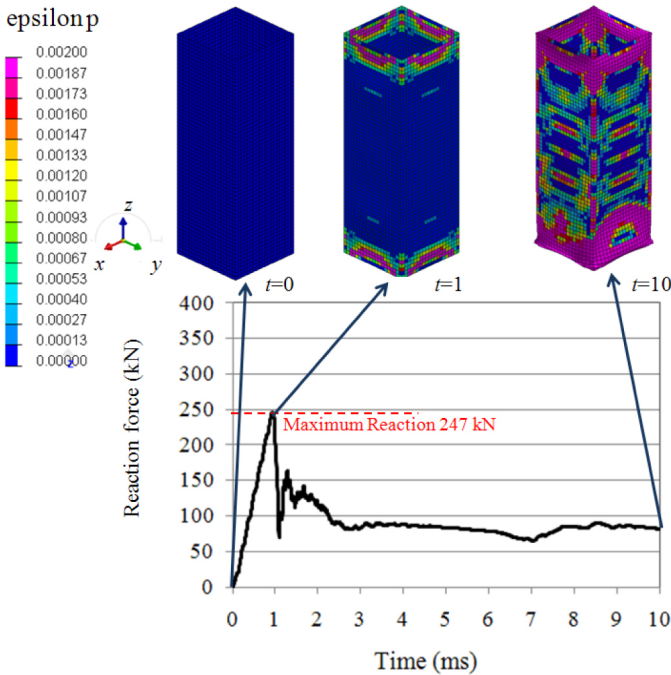


Figure 3. Time history of reaction force of a rectangular thin-shell beam at $v = 1$ m/s and deformation modes at some representative times.

Figure 4 shows the reaction force generated in the beam when the loading rate was varied in a range from 0.0001 m/s (0.00036 km/h) to 30 m/s (108 km/h). The vertical axis shows the reaction force normalized to the reaction force (400 kN) at the time the entire cross section reached its yield strength. The following characteristics can be seen in Fig. 4.

- (1). Above a loading rate of 10 m/s, the reaction force exceeds the load (400 kN) at the time the entire cross section reaches a state of uniform yield stress. This characteristic will be described in more detail later.
- (2). The reaction force converges to almost a uniform level at loading rates less than 0.03 m/s.

First, we will examine the second characteristic here by making a comparison with the reaction force seen for Euler's buckling solution and that for von Karman's effective width solution. Von Karman's effective width expression assumes a

flat plate that is simply supported at both ends. It is often used as an approximate solution when designing structures composed of thin flat plates. The reaction force calculated in this analysis is considerably larger than the level seen for Euler's buckling solution (51.5 kN). It also converges between the value of 145 kN obtained with von Karman's effective width expression at a buckling coefficient $\kappa=4$ and the value of 94.5 kN obtained at $\kappa=1.7$. These results imply that the minimum reaction force can be estimated by assuming von Karman's effective width solution at $\kappa=1.7$, but that an increase in reaction force proportional to the loading rate must be taken into account in order to design safer rectangular thin-shell structured beams. A detailed comparative study of these two fundamental solutions will be continued in the next section concerning the low loading rate region. An explanation of the first characteristic above concerning overshooting of the reaction force under high loading rates will be given later in the section dealing with the high loading rate region.

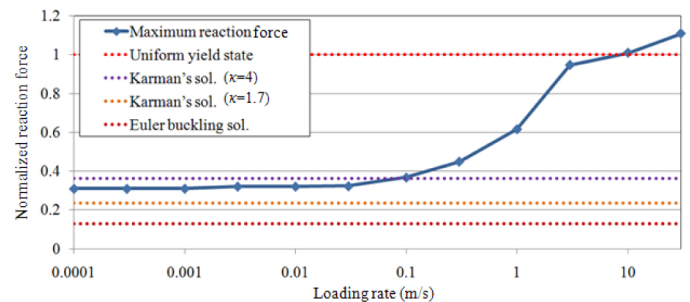


Figure 4. Loading rate dependence of rectangular thin-shell structured beam.

The Euler buckling load is found with the following equations⁽¹⁴⁾.

$$\sigma_{cr} = \frac{\pi^2 \times E}{12 \times (1 - \nu^2)} \times \left(\frac{h}{a}\right)^2 \times k_{cr} \quad (1)$$

$$k_{cr} = \left(\frac{ma}{b}\right)^2 + 2 + \left(\frac{b}{ma}\right)^2 \quad (2)$$

Substituting the values of mode order $m = 3$, Young's modulus $E = 206$ GPa, Poisson's ratio $\nu = 0.3$, width $a = 100$ mm, height $b = 300$ mm and plate thickness $h = 1.2$ mm into these equations results in $k_{cr} = 4.0$, and the buckling load is found to be $P_{cr} = 4a \times h \times \sigma_{cr} = 51.5$ kN.

LOW LOADING RATE REGION

Figure 5 shows the out-of-plane deformation modes in the vicinity of the maximum reaction force (129 kN) generated for loading point displacement of 1.4 mm ($t = 140$ ms) at a loading rate of 0.01 m/s. In the region regarded as being