AXIAL COLLAPSE OF SQUARE TUBES WITH SHORT LENGTH

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ABSTRACT

In order to reduce high impact load occurring in axial collapse of a crush can, which is installed in the front part of car, the elastoplastic nonlinear behavior of short thin-walled frusta with square cross-section subjected to statically axial compression is studied by using finite element method. The square tubes 1.8mm in thickness, with upper cross-section of 85mm x 90mm and lower cross-section of 130mm x 135 mm, have different lengths ranging from 135mm to 225mm. A typical tensile stress-strain curve for aluminum is modeled as 2 straight-line hardening relationship.

The FEM code MSC.Marc is used to simulate the axial compression of thin-walled frusta of square cross-section. The load-displacement curves of frusta are obtained from the numerical analyses. It is found from the curves that in the axial collapse process of the frusta there are two peaks of the load, corresponding to the initial buckling and formation of the second wrinkle. Unlike the axial collapse of long tubes, however, the load due to the second wrinkle is higher in magnitude than the initial buckling load. The reason for high second peak load is that the frusta are too short to form the 2nd wrinkle.

The second peak load is very sensitive to the boundary condition on the lower end. Usually, high load occurs in a strong restraint.

Also, it is found the effects of holes in side plate of frusta on the second peak load are very complex. If the holes were located exactly right on the folding lobes, the second peak load could be reduced. The other methods to reduce the second peak load were also investigated. It seems that the most effective method for lowering load is shortening the wavelength of wrinkles.

INTRODUCTION

In the development of vehicle crashworthiness, crush can, which is located in bumper, must strike a balance between high energy absorption to secure reparability in low-speed crash and frame resistance in high-speed crash. In particular, in order to satisfy reparability while maintaining good styling, crush can should be as short as possible while being able to absorb energy efficiently. In this paper, influence of length and restraint condition on crush characteristics was studied using a base geometry simulating crush can. Besides, geometry variations were also studied to absorb energy efficiently.

Method and Model of Analysis

In this analysis, generic FEM analysis software MSC.Marc was used to analyze the axial compression of an analytical model (Figure 1) representing the aforementioned simplified model. A square tube was modeled with 3D quadrilateral shells and its bottom was completely fixed to a rigid wall. The square tube was compressed by pressing the rigid body against its top with displacement control, taking into consideration the friction coefficient between the rigid body and the top of square tube. The dimensions of base model are shown in Figure 1. The model is 1.8mm in thickness and made of 440Mpa steel plate.

The characteristics of the simplified model were studied by changing the length of square tube, restraint conditions, etc. from the base model. Though the crush behavior of square tube also relates to the impact speed, quasi-static crush was studied since the characteristics at low speed are similar to quasi-static crush and the characteristics at low speed are also related to quasi-static crush.

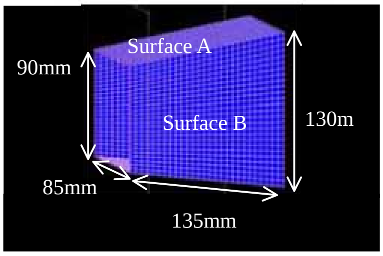

Figure 1.　Analytical model

A homogeneous isotropic elasto-plastic body conforming to Von Mises yield criterion was used for the analysis so that stress σ and strain ε can be approximated by 2 straight-line hardening relationship. σ_y, E, and E_h represent yield stress, longitudinal elastic modulus, and work hardening respectively. In this study, material Poisson's ratio ν = 0.3, longitudinal elastic modulus E = 70.6 (GPa), and yield stress σ_y = E/1000 and work hardening characteristics E_h is used for the influence of material characteristics. Though actual material may not be approximated by 2 straight-line hardening relationship, the influence of magnitude of work hardening on the crush characteristics can be represented by the effect of work hardening characteristics E_h obtained here.

Analysis Results of Base Model

Figure 2 and 3 show the relationship between compressive load and axial displacement of base model in axial compression and its deflection. In Figure 2 and 3, after high peak load was generated, deformation progressed with fluctuation of load. Once the first wrinkle collapsed, the second wrinkle was generated. At that time, a load generated by the second wrinkle was higher than the first peak load.
At the early phase of deflection, the load fluctuated due to the influence of contact condition between rigid body and component.

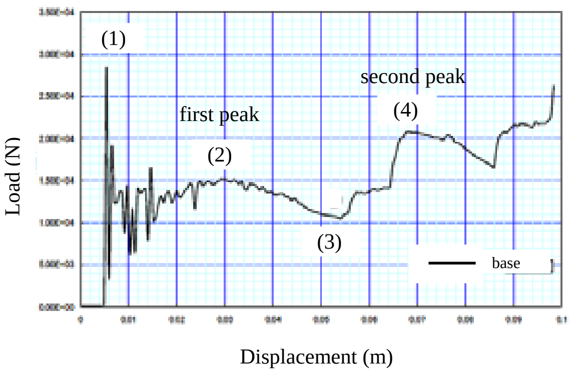

Figure 2.　Load-deflection curve of base model

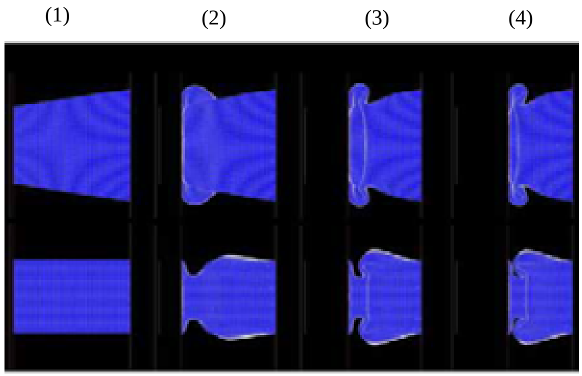

Figure 3.　Deflection of base model

Study on the Length of Model

The length of model was changed to 180mm and 225mm from base model with its angle fixed ($\theta=\tan^{-1}(20/135)$).

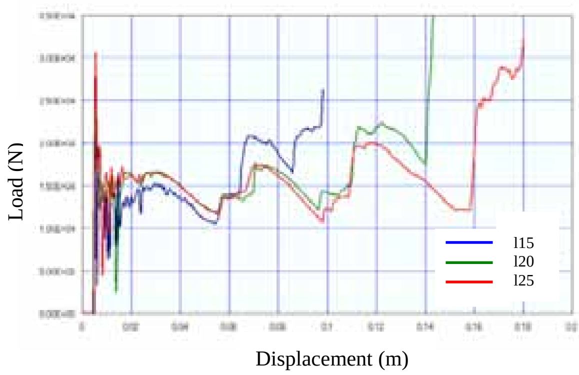

Figure 4.　Load-deflection curve of model length changed

Figure 4 shows the relationship between compressive load and axial displacement in axial compression of a square tube extended. Table 1 shows the length of first wrinkle.
As shown in this table, with longer component such as model l20 (L=180mm) and model l25 (225mm), the wrinkle and amplitude of load-deflection curve become longer.

Table 1.　Length of first wrinkle

Model	Wrinkle Length(mm)
l15	65
l20	70
l25	70

Based on the results, remaining length of component is predicted as shown in table 2. Since model l20 and model l25 have a length enough to generate the second wrinkle, the similar load-amplitude curve is obtained for the first and second wrinkle. In case of base model, with remaining length of 5mm, the second wrinkle was not made like the first one since its end was restrained. As a conclusion, its length is not enough to generate the second wrinkle. Therefore, in case of base model, the second peak load rose significantly since collapse margin is insufficient to generate a wrinkle and its bottom restraint hinders deflection that leads to wrinkle. This is also obvious from the difference in the third load amplitude between model l20 and model l25.

Table 2. Length of the first wrinkle

Model	Wrinkle Length(mm)	Remaining Length(mm)
l15	65	5
l20	70	40
l25	70	85

The axial compression of square tube can be categorized into three types depending on its length in axial direction.

(1) A square tube long enough to generate more than three wrinkles
In this case, with less influence of bottom restrain, wrinkles are generated one after another with its length controlled automatically; thus, the load does not rise due to the last wrinkle generation.

(2) A short square tube that cannot generate a wrinkle
In this case, the deflection is similar to that of a plate as circumferential wrinkle is be made.

(3) A square tube with one or two wrinkles
Without a length enough to generate the second wrinkle, load generated by wrinkle becomes high with great influence of restraint.

Since the base model falls within category (3), it is subject to the influence of restraint; thus, it is very important to adjust the length of wrinkle.

Study on Influence of Restrain Condition

The results of study on the influence of restraint condition are described in this section. Figure 5 shows respective restraint conditions that were studied.

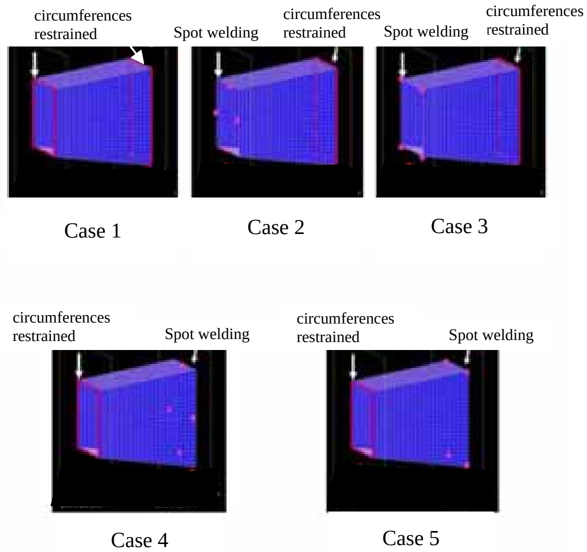

Figure 5. Restraint condition

Table 3 shows the measurement results of length of wrinkle generated in cases 1 through 5. Figure 6 shows the measurement positions of individual wrinkles. Figure 7 shows load-deflection curve of cases 1 through 3. Figure 8 shows load-deflection curve of case 1, case 4, and case 5.

Table 3. Length of first wrinkle

Model	Wrinkle Length(mm)
1 (Top & bottom circumferences restrained)	65
2 (Top center restrained)	80
3 (Top corner restrained)	80
4 (Bottom center restrained)	67.5
5 (Bottom corner restrained)	65

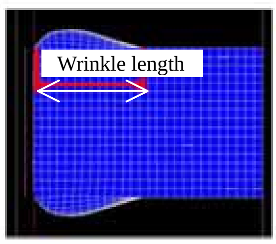

Figure 6. Measurement position of wrinkle length

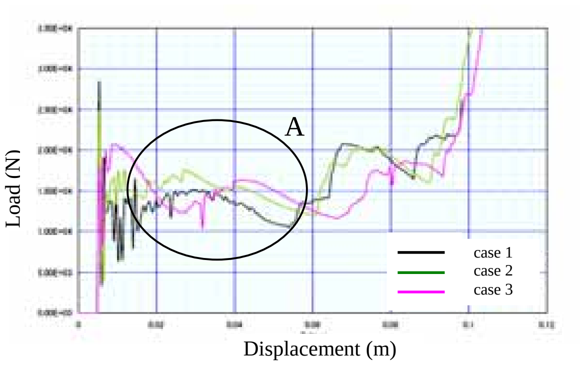

Figure 7. Load-deflection curve of model with restraint condition of contact surface varied

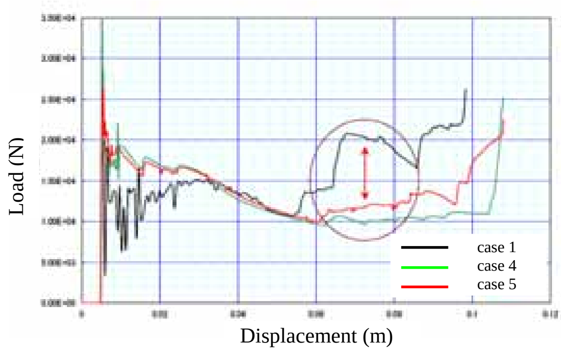

Figure 8. Load-deflection curve of model with different restraint conditions of restrain surface varied

The analysis results show:

(1) The influence of restraint condition is complicated since the length is short.

(2) The behavior of first wrinkle generation depends on the restrain around starting point.

(3) As shown in portion A in Figure 7, the weaker the restrain is, the longer the first wrinkle becomes. Consequently, load of the second wrinkle varies. (Case 3 does not have the second peak load since it does not have length enough to generate the second wrinkle.

As shown in portion B in Figure 8, the restraint at the end has a great influence on last load increase at the end of compression. Generally, the load decreases as strain becomes weaker.

A Model with Holes Locally

In order to reduce the peak load, holes (10mm X 10mm square holes in the center of surfaces A and B) were made around wrinkle peak in base model as shown in Figure 9.

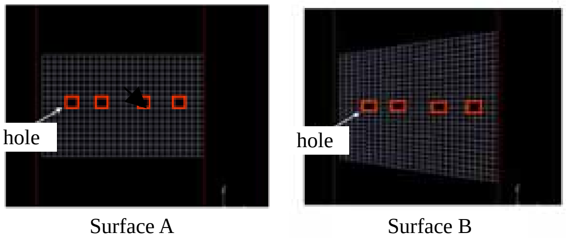

Figure 9. Geometry of analytical model with holes

Figure 10 shows the analysis result. Figure 11 shows the deflection. Points (1) through (4) shown in Figure 10 correspond to numbers shown in Figure 11. These figures indicate that, by making local holes, the second peak load can be reduced. The effect of local holes, however, is only limited to the case where the location of wrinkle is predictable. It is still not sure whether the same effect is expected in a complicated load input or oblique impact. If the number of holes is increased, it may intentionally reduce the energy absorption area.

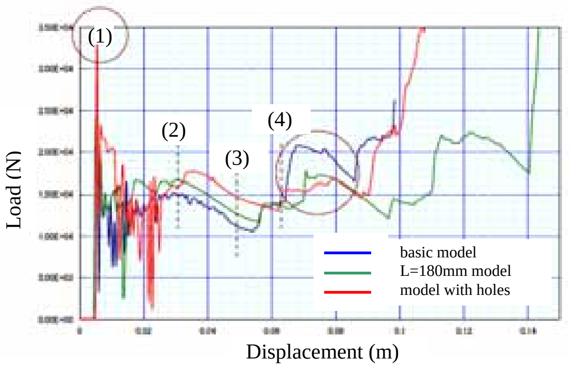

Figure 10. Load-deflection curve of model with holes

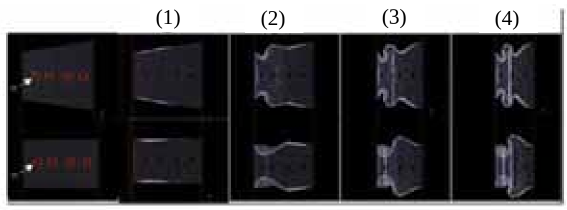

Figure 11. Deflection of model with holes

Model with Corrugation in Axial Direction

Chen [2006] elucidated the following three deflection modes of a square tube:

(1) N mode: a mode where no deflection is generated along corrugation

(2) S mode (Simultaneous Crush): a deflection mode along corrugation where a load monotonically increases.

(3) P mode (Progressive Crush): a deflection mode along corrugation with load amplitude

S mode is favorable since no peak load is generated at initial phase. The load monotonously increases in compression with small load amplitude, and so on. Though corrugation may decrease energy absorption rate compared with the conventional square tube, it has been proven out that by optimizing the geometry, the equivalent effect as the conventional one can be obtained.

Therefore, a study was made to figure out whether the corrugate square tube is applicable as a refinement of the base model.

Three geometries were studied with regular corrugation of wave amplitude of 2a and a sin functional curve of y=asin (2πλ), where a, λ is amplitude and wavelength respectively. Figure 12 shows load-deflection curve of individual models, and Figure 13, 14, and 15 show their deflection.

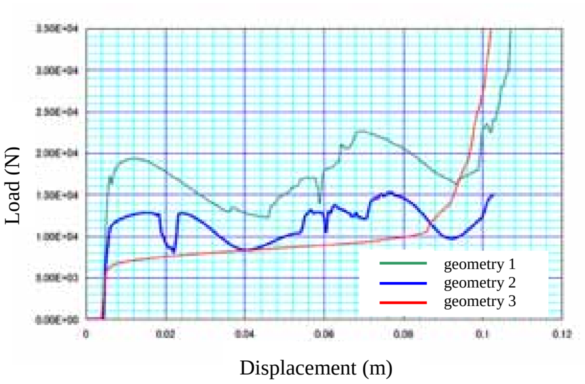

Figure 12. Load-deflection curve of geometry 1, 2 and 3

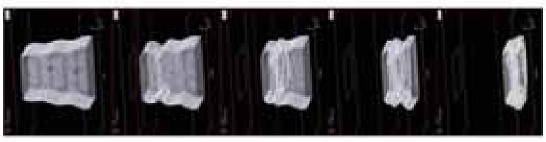

Figure 13. Deflection of geometry 1

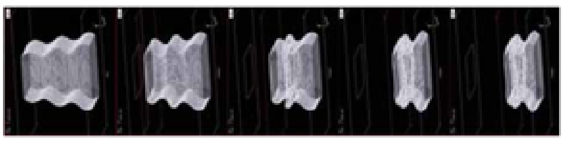

Figure 14. Deflection of geometry 2

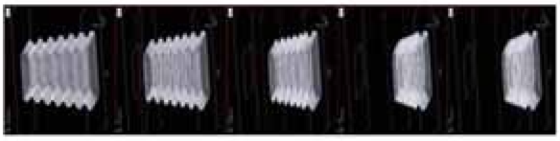

Figure 15. Deflection of geometry 3

As is indicated in load-deflection curve in Figure 12 and deflection in Figure 13 though 15, geometry 3 resulted in S mode. As was mentioned, however, geometry 3 resulted in the lowest average load among those 3 geometries. Though this geometry with corrugation is able to obtain S mode, the design must be optimized in order to control deflection mode and to have high energy absorption rate.

CONCLUSION

The following conclusions have been obtained from analytical results.

(1) Length of component

As a short square tube, the base model does not have enough length to generate the second wrinkle; thus, the second peak load rises. Control is required so that the second wrinkle can be generated.

(2) Influence of restraint condition

With short overall length of square tube, the influence of restraint condition is complicated; thus, it is difficult to cope with the issue by changing restraint condition.

(3) Study on geometry change

-A model with holes locally

The second peal load is decreased by having holes. However, it is not desirable solution since this is only applicable to the case where wrinkle position can be predicted and this may lead to the initial peak load increase.

-A model with corrugation in axial direction

By having corrugation, such a deflection mode is obtained that the load monotonously increases without initial peak load. It is, however, difficult to apply the geometry studied as it is. The fact that wrinkle length can be controlled with the corrugation could be a clue for the improvement of component.

REFERENCES

[1] Tokyo University of Science, Deiheng Chen and Takeshi Hiratsuka. 2006. “Study of Axially Crushed Cylindrical Tubes with Corrugated Surface Based on Numerical Analysis”, Transactions of the Japan Society of Mechanical Engineers, Series A, Vol.72, No.722 (2006), pp.1464-1471.