

Development of Orthotropic Damage Model for Crush Simulation of Extruded Aluminum Member

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ABSTRACT

It is well known that an extruded aluminum member has the different mechanical characteristics between the axial direction and the normal direction. It is important to consider the extruded direction dependence of mechanical characteristics in evaluating the energy absorption performance of the extruded aluminum member at non-uniform loading directions. For simulating such an orthotropic mechanical characteristic, the simple orthotropic damage model was proposed with the simulation method. The test specimens were cut out of the axial aluminum member in the axial and normal directions. The tensile, three-point bending and mixed-mode fracture tests were conducted in order to obtain the orthotropic characteristics. The simple orthotropic damage model was proposed and applied to the crush behavior of the extruded aluminum member. The load displacement curve and damage zone development were compared with those obtained by the experiments. As a result, the usefulness of the orthotropic damage model and simulation methods were validated.

1. Introduction

The mechanical properties of extruded aluminum members are known to differ in the axial and normal directions. It has been considered useful to develop a simulation method that takes this fact into consideration, for use in the evaluation of the energy absorption performance of extruded aluminum members under loads applied from various directions. A considerable amount of research has been conducted to characterize the impact energy absorption of extruded aluminum members and develop the simulation methods^{(1)-(6), (8), (9)}. The energy absorption characteristics of extruded aluminum members under various load conditions has been evaluated⁽¹⁾⁻⁽⁶⁾, and simulation methods that consider the orthotropic mechanical properties of the extruded aluminum members have been developed⁽⁷⁾⁻⁽⁹⁾, but the focus of research has been limited to microscopic deformation.

The research discussed in this paper therefore set out to develop a simple damage model that considered orthotropic mechanical properties in extruded aluminum members and to use this model in developing a simulation method. First, test specimens were cut of an extruded aluminum member in the axial and normal directions and subjected to tensile and three-point bending tests to

characterize the orthotropic mechanical properties of the material. In addition, mixed-mode fracture tests were conducted to measure the stress intensity factor in the mixed mode, in consideration of the complexity of the stress state at the points at which cracks initiate during crush deformation of an extruded aluminum member. The orthotropic mechanical properties measured by tensile and three-point bending tests are analyzed so that the material model would be proposed. Finally, numerical simulations of crush tests on extruded aluminum members were conducted using the simple orthotropic damage model that had been developed. The validity of the new method was then verified by comparison of simulation results with test results.

2. Material Constitutive Law

To simplify the material model employed in this research, the linear elastoplastic model expressed by Eq. (1) was used. Figure 1 shows an illustration of the model.

$$\sigma = a + b\bar{\epsilon}_p \quad (1)$$

Here, a is the yield stress, b is the strain hardening parameter, and $\bar{\epsilon}_p$ is the equivalent plastic strain. The simulation used in this study is conducted on the plane

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stress conditions, and the equivalent plastic strain is therefore given by Eq. (2).

$$\bar{\varepsilon}_p^2 = 4/3(\varepsilon_{xx}^2 + \varepsilon_{xx}\varepsilon_{yy} + \varepsilon_{yy}^2) + 1/3(\varepsilon_{xy}^2 + \varepsilon_{yz}^2 + \varepsilon_{zx}^2) \quad (2)$$

Here, ε_{ii} are the tensile plastic strain components in each direction, and ε_{ij} are the shear plastic strain components.

The relationship between stress and strain in the material is given by the following equations, based on the total strain theory:

$$\varepsilon_{all} = \varepsilon_e + \varepsilon_p \quad (3)$$

$$\sigma = E(1 - D)\varepsilon_e \quad (4)$$

$$\varepsilon_p = (\sigma - a)/b \quad (5)$$

Here, ε_{all} is the strain vector, σ is the stress tensor, and E is the elastic matrix.

The isotropic linear damage model proposed by Johnson and Cook⁽¹⁰⁾ was used as a reference in formulating the orthotropic damage model used in the simulation, which is expressed by the following equations:

$$D = \int_{\bar{\varepsilon}_1}^{\bar{\varepsilon}_2} 1/\bar{\varepsilon}_p d\bar{\varepsilon}_p \quad (6)$$

$$\bar{\varepsilon}_1 = 2/\sqrt{3} \{c_{1xx}\varepsilon_x^2 + c_{1xy}\varepsilon_x\varepsilon_y + c_{1yy}\varepsilon_y^2 + 1/4(c_{1xy}\varepsilon_{xy}^2 + c_{1yz}\varepsilon_{yz}^2 + c_{1zx}\varepsilon_{zx}^2)\}^{1/2} \quad (7)$$

$$\bar{\varepsilon}_2 = 2/\sqrt{3} \{c_{2xx}\varepsilon_x^2 + c_{2xy}\varepsilon_x\varepsilon_y + c_{2yy}\varepsilon_y^2 + 1/4(c_{2xy}\varepsilon_{xy}^2 + c_{2yz}\varepsilon_{yz}^2 + c_{2zx}\varepsilon_{zx}^2)\}^{1/2} \quad (8)$$

; where D is the orthotropic damage parameter, $\bar{\varepsilon}_1$ is the equivalent plastic strain at the initiation of damage, and $\bar{\varepsilon}_2$ is the equivalent plastic strain when damage ceases to occur. c_{ijkl} and c_{2ijkl} are orthotropic parameters. The use of different weight functions for the strain components in each direction enables their effect on the overall strain to be adjusted. Orthotropy can be treated phenomenologically by controlling the degree of contribution of these equivalent strains. In the present simulation, the material fractures when D reaches 1; when D reaches 1 at the integration points of the shell elements in the direction of thickness, the stress tensor at those integration points is calculated as 0. In addition, a multilayered integration

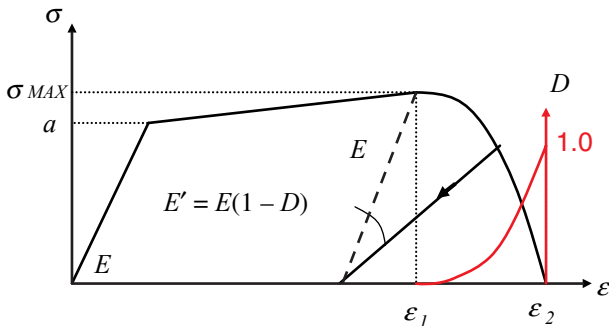


Fig. 1 Illustration of material model with damage

point determination method is used in which the shell elements are eliminated when D reaches 1 at all the shell element integration points. This enables simple expression of the initiation and propagation of cracks.

The material law was incorporated as a user subroutine of the general explicit solver RADIOSS Ver4.4 in the finite element models. Figures 2 and 3 show finite element models of a three-point bending test and an extruded aluminum crush test respectively. The models employed Belytschko shell elements, and five integration points were used in the direction of thickness.

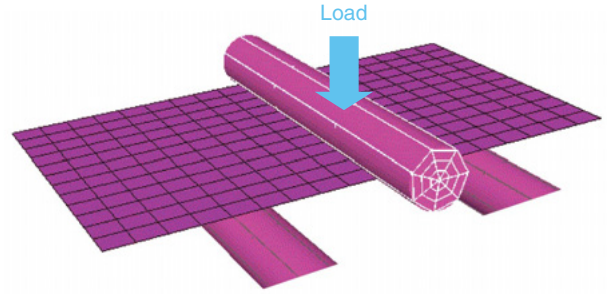


Fig. 2 Finite element model of three-point bending test

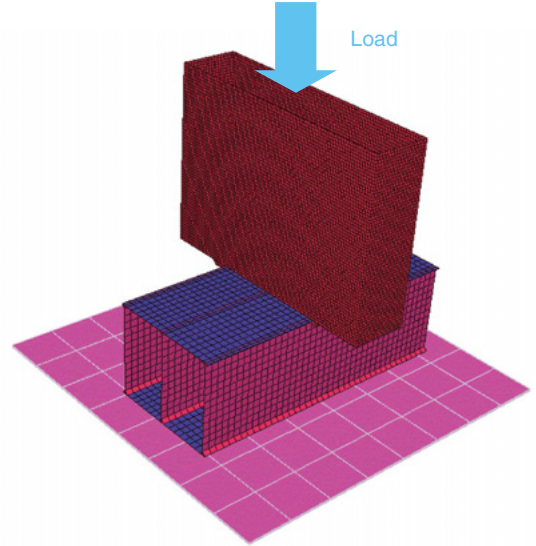


Fig. 3 Finite element model of aluminum extrusion crush test

3. Test Method

3.1. Test Material and Test Specimens

Extruded A6061-T6 aluminum alloys were used in the tests. Tensile, three-point bending, and mixed-mode fracture test specimens were cut in the axial and normal directions from thin rectangular pipes with closed cross-sections, formed from sheets of 2 and 3 mm in thickness. Table 1 shows the chemical compositions of the test

Table 1 Chemical composition of A6061 (wt. %)

Si	Fe	Cu	Mn
0.40-0.80	0.7	0.05-0.20	0.15
Mg	Cr	Zn	Ti
0.08-0.12	0.04-0.35	0.25	0.15

material. Two chemical compositions, using different ratios of Mg and Si, were used in the tests to understand the ductile material and brittle material behaviors. Composition A used small amounts of Mg and Si, while composition B used large amounts. The materials were aged for 3 hours at 190 °C. Figure 4 shows the geometry of the tensile test specimens, cut out of thin sheets (2 mm) in accordance with the specifications of JIS Z2201 14B. Thin oblong sheets ($L = 40$, $w = 20$, $t = 2$ mm) were used in the bending test. Figure 5 shows the geometry of the mixed-mode fracture test specimen proposed by Richard⁽¹¹⁾. The pre-crack was introduced by the fatigue test based on the specifications of JSME S001-1992. The extruded aluminum crush test specimens were 200 mm in length, and cut from a thin rectangular pipe with a closed cross-section.

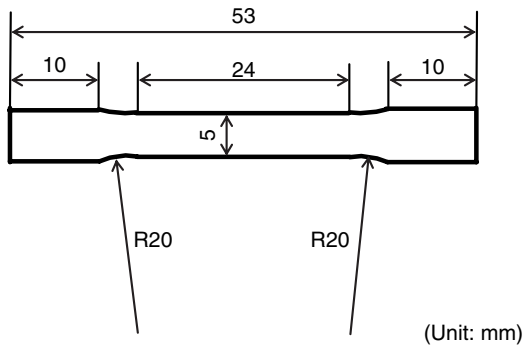


Fig. 4 Schematic illustration of tensile test specimen

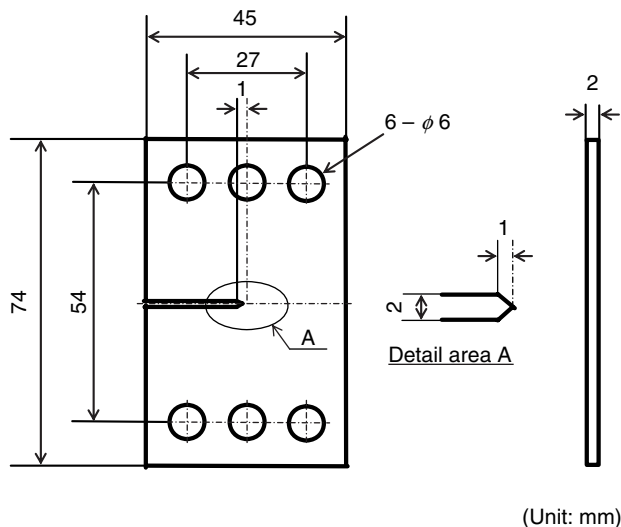


Fig. 5 Schematic illustration of mixed-mode fracture tests specimen

3.2. Test Equipment and Method

3.2.1. Tensile and three-point bending tests

A general screw driven test device manufactured by Shimadzu Corporation (rated capacity: 5 kN) was used in this research to measure quasi-static stress-strain behavior. A tensile speed of 0.5 mm/min was applied. A wedge speed of 50 mm/min was applied in the three-point bending test, and the load applied by the wedge and the displacement were measured. Figure 6 shows a photograph of the three-point bending test device.

3.2.2. Mixed-mode fracture test

Fracture tests were conducted using a mixed-mode fracture test jig (Fig. 7) in the same general screw driven test device used for the tensile and bending tests. Equation 9 defines the stress intensity factor, K , which is used for evaluating the stress state at the crack tip when the crack begins to initiate. This is the finite element analytic solution formulated by Richard and Benitz⁽¹²⁾. Suffix I and II indicate mode I, the fracture state under tensile predominance, and mode II, the fracture state under shear predominance.

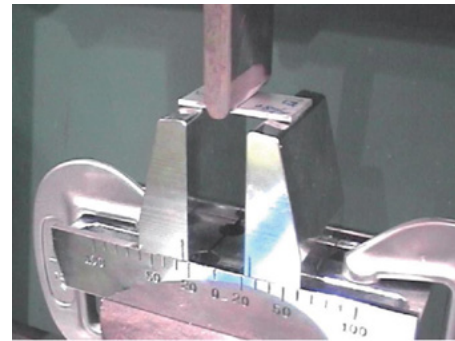


Fig. 6 Photograph of bending test device

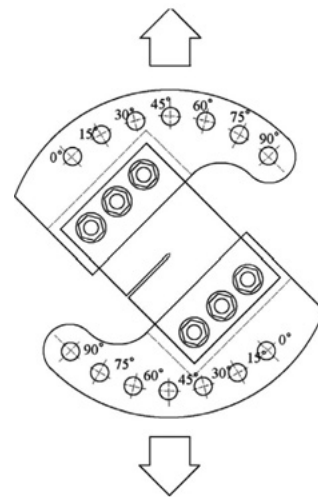


Fig. 7 Schematic illustration of mixed-mode fracture test device

$$K_{I,II} = F_{I,II} P / WB \sqrt{\pi a} \quad (9)$$

W is the width of the test specimen, B is the thickness of the test specimen, a is the length of the pre-crack, and P is the load. F_I and F_{II} are correction factors determined by the axial angle of the load and the length of the pre-crack.

During the tests, the pre-crack tip was monitored using a video microscope (Scala VMS-3000), and the initiation and propagation of cracks were measured. Figure 8 shows a photograph of the test device.

3.2.3. Crush test of extruded aluminum member

Crush tests of extruded aluminum members were conducted as component-level tests. Figure 9 shows a photograph of the test device. Extruded aluminum members were fixed in an iron jig and crushed by a square, columnar compression jig moving at 100 mm/min. A home video camera was used to record the deformation of the member and the development of cracks.

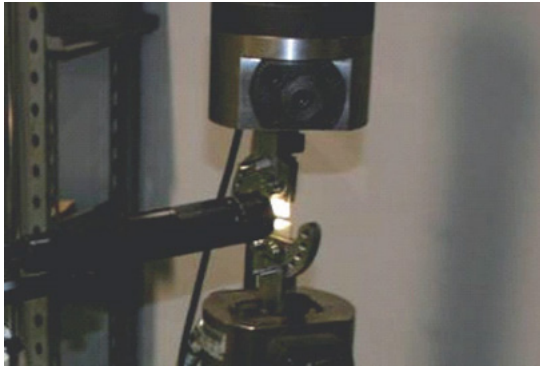


Fig. 8 Photograph of mixed-mode fracture test device

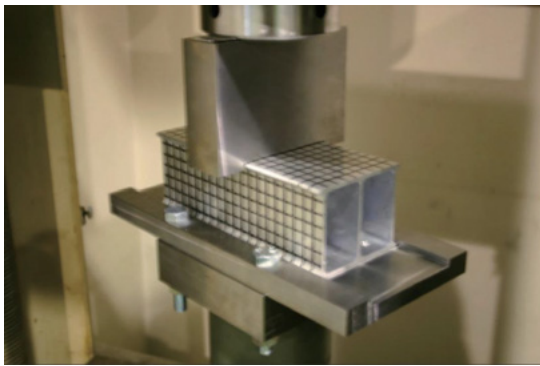


Fig. 9 Photograph of crush test device

4. Test Results and Consideration

4.1. Tensile Test Results

Table 2 shows the mechanical properties of compositions A and B, as determined from tensile test

Table 2 Mechanical properties

	Composition A		Composition B	
	Axial	Normal	Axial	Normal
Elastic modulus (MPa)	70.5	70.8	71.4	70.1
Yield stress (MPa)	278	270	303	291
Tensile strength (MPa)	316	311	336	331
Rupture stress (MPa)	270	264	296	308

results. Figures 10 and 11 show the stress strain curves of compositions A and B, respectively. There are slight differences in the stress values for the axial and normal directions, but no major differences are observed. As shown in Fig. 10 also indicates that orthotropy can be ignored in terms of yield stress and tensile strength. Composition A, however, did display a higher fracture strain than composition B, and displayed more ductile fracture behavior than composition B. Composition B, with a higher ratio of Mg and Si than composition A, recorded higher stress values than composition A.

4.2. Three-point Bending Test Results

Figures 12 and 13 show the relationship between load and displacement of the bending test for compositions A and B respectively. For both compositions, fracture displacement was greater in the axial than in the normal direction. The effect of orthotropy, which was negligible in the tensile tests, was prominent in the bending tests. In addition, composition A displayed greater ductility than

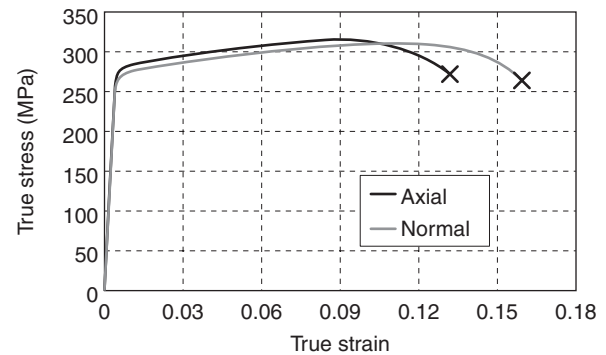


Fig. 10 Stress-strain curves of composition A

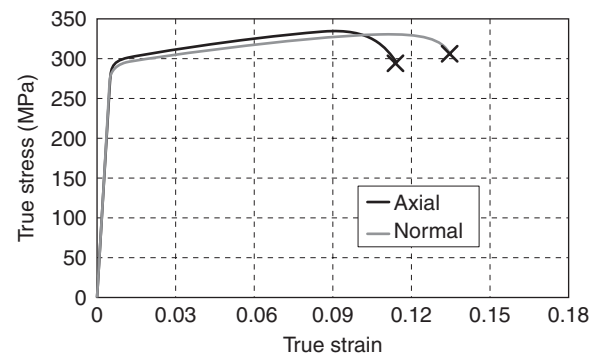


Fig. 11 Stress-strain curves of composition B

composition B, which contained a higher ratio of Mg and Si. Previous research⁽¹³⁾⁻⁽¹⁵⁾ has indicated that the particles of additives such as Si in Mg-Si aluminum alloys become the point of initiation of cracks, and this research produced identical results. Figure 14 shows the photograph of the backside of the bending specimen of composition A after three-point bending test. The area indicated in Fig. 14 was observed by a scanning electron microscopy (JEOL JSM-5300T). Figure 15 shows a scanning electron micrograph of the backside of the composition A test specimen cut in the axial direction after the bending test. Figure 16 shows the same for the composition A test specimen cut in the normal direction after the bending test. As Fig. 15 shows, the fractures in the test specimen are caused by tensile loading from the outer most layer, and numerous microscopic cracks can

be observed on the surface. By contrast, in the test specimen cut in the normal direction, fracture surfaces are formed tilted in the direction of thickness along shear bands, and localization of strain has occurred. This difference in fracture pattern is considered to cause the orthotropy observed in the three-point bending test results.

4.3. Mixed-mode Fracture Test Results

Stress intensity factors for the pre-crack tip were determined from the load-displacement curve and crack initiation points observed in mixed-mode fracture tests. Figures 17 and 18 show the stress intensity factors for compositions A and B respectively. Overall, stress intensity factors are higher for composition A than composition B, a result which supports the results of the three-point bending tests, in which composition A displayed more ductile fracture behavior than composition B. Comparing the stress intensity factors for each composition in the axial and normal directions, the stress intensity factor was higher for the axial than the normal direction for the stress state in which mode I was dominant, but the difference between the stress intensity factors in the axial and normal directions decreases as the mode II components increased. The stress state at the point of crack initiation in the three-point bending tests was close to mode I, but the dominant stress state at the

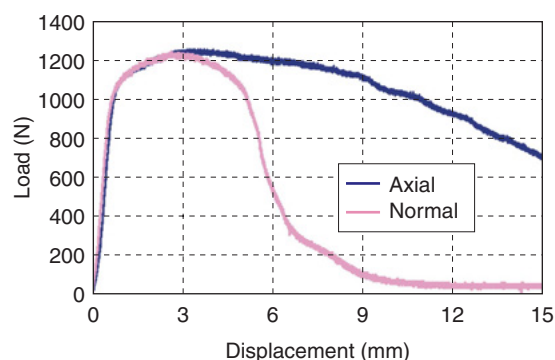


Fig. 12 Load displacement histories of composition A

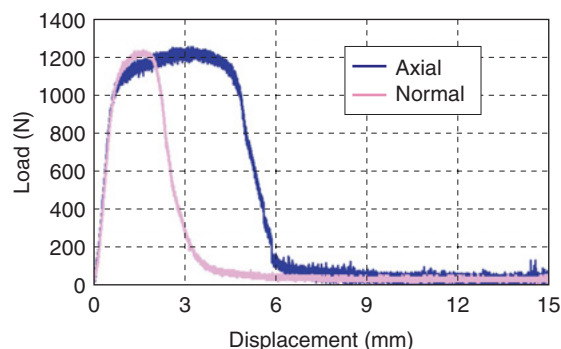


Fig. 13 Load displacement histories of composition B

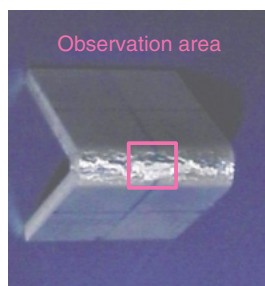


Fig. 14 Specimen of composition A after bending test

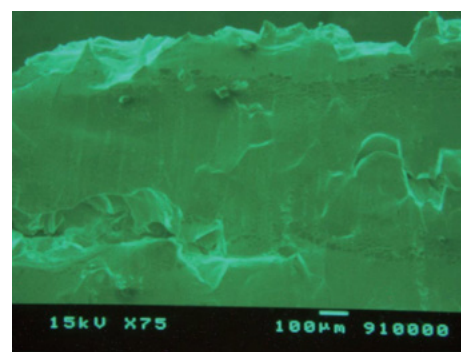


Fig. 15 SEM photograph of composition A cut in the axial direction after bending test

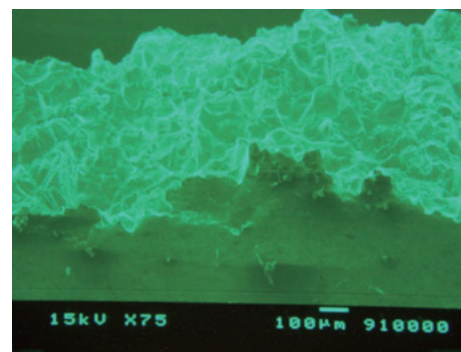


Fig. 16 SEM photograph of composition A cut in the normal direction after bending test

point of crack initiation in the tensile tests was considered to be the mode II state, when shearing predominates, rather than pure mode I. This is believed to be the cause of the mixed-mode fractures. These test results indicated that it is most reasonable to establish material parameters for an orthotropic damage model on the basis of the results of three-point bending tests, in which the effect of orthotropy is dominant.

4.4. Extruded Aluminum Member Crush Test Results

Figure 19 shows the compression load-displacement curve obtained from crush tests. As in the three-point bending tests, the maximum load for composition A was lower than for composition B. Figures 20 and 21 show extruded aluminum members following the tests. The crack of composition A did not reach the end area of the extruded aluminum members, however, the crack of composition B reached the end area. Therefore, composition A showed more ductile fracture behavior, with brittle fracture behavior observed in composition B.

4.5. Comparison of Three-point Bending Test and Simulation

All of the material parameters in the material constitutive law used in the simulations, with the

exception of the orthotropy parameters, were identified on the basis of the results of tensile tests. A set of orthotropic parameters was determined so as to ensure that simulation results for load-displacement curves corresponded well with the results of the three-point bending tests. Table 3 shows the material parameters identified for compositions A and B. Figures 22 and 23 compare the results of simulations of three-point bending tests using these parameters with the results of actual tests for compositions A and B respectively. The results show that the orthotropic damage model proposed in this research has simulated the orthotropy observed in actual test results at

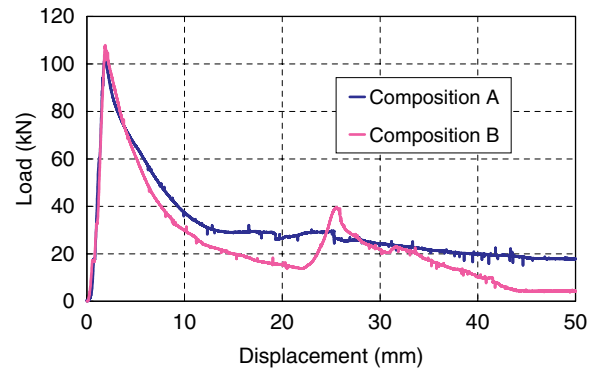


Fig. 19 Load displacement histories of crush tests

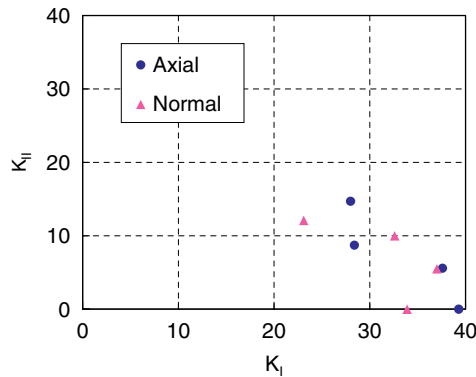


Fig. 17 Mixed-mode stress intensity factors of composition A

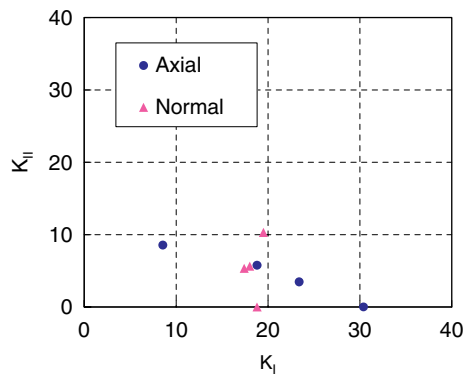


Fig. 18 Mixed-mode stress intensity factors of composition B

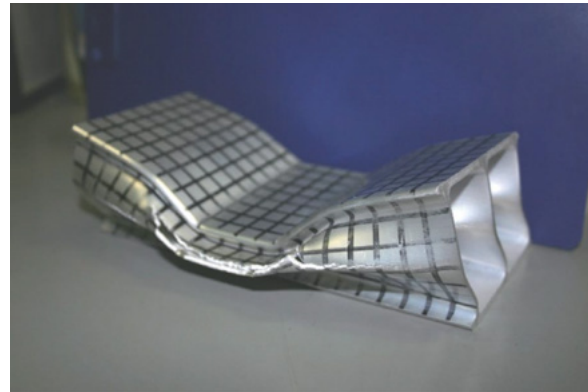


Fig. 20 Composition A after crush test

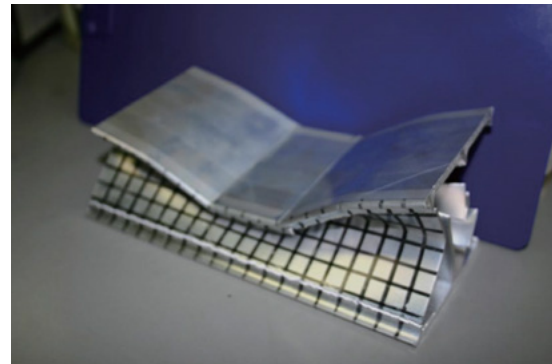


Fig. 21 Composition B after crush test

Table 3 Material parameters

	Composition A	Composition B
Elastic modulus (GPa)	71	71
Yield stress (MPa)	290	310
Strain hardening parameter	420	420
ϵ_1	0.19	0.09
ϵ_2	0.27	0.095
C_{1xx}	0.401	0.184
C_{1xxy}	0.633	0.429
C_{1yy}	1	1
C_{1xy}	1	1
C_{1yz}	1	1
C_{1zx}	1	1
C_{2xx}	0.071	1
C_{2xxy}	0.267	1
C_{2yy}	1	1
C_{2xy}	1	1
C_{2yz}	1	1
C_{2zx}	1	1

the high accuracy. In addition, the simulation accuracy was low when material parameters based only on the results of tensile tests, without consideration of orthotropy.

4.6. Comparison of Extruded Aluminum Member Crush Test and Simulation

Figure 24 compares the results of extruded aluminum crush tests and numerical simulations conducted using the

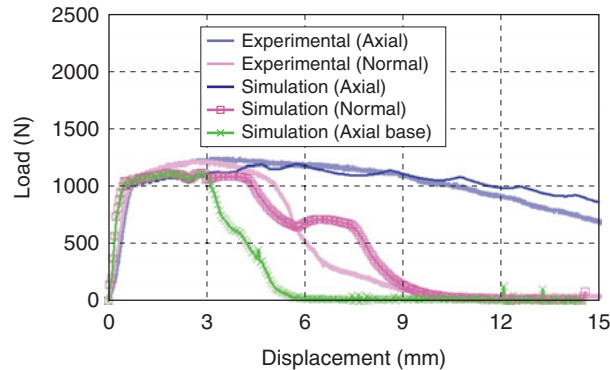


Fig. 22 Bending load displacement curves of composition A

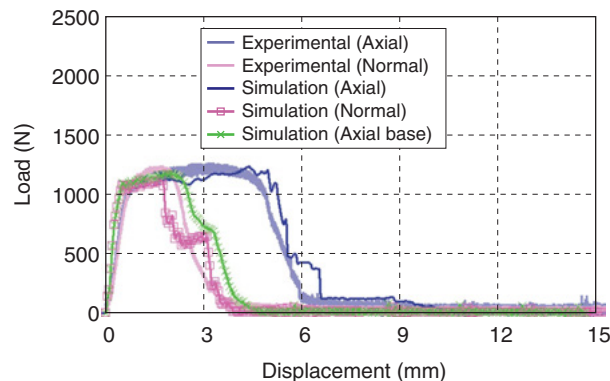


Fig. 23 Bending load displacement curves of composition B

set of material parameters established in this research. For both compositions A and B, the load-displacement histories simulated by using the new parameters show better agreement with the experimental result compared with those of a conventional simulation that does not consider orthotropy. Figure 26 shows the distribution of equivalent plastic strain simulated for composition A. Figure 27 shows a photograph of an extruded aluminum member after a crush test. As Figures 26 and 27 indicate, the simulation was able to reproduce test results in terms of deformation mode and areas in which cracks were initiated with a high degree of accuracy. This suggests that the orthotropic damage model proposed in this research enables simple simulation of crack initiation and development following the point of maximum load.

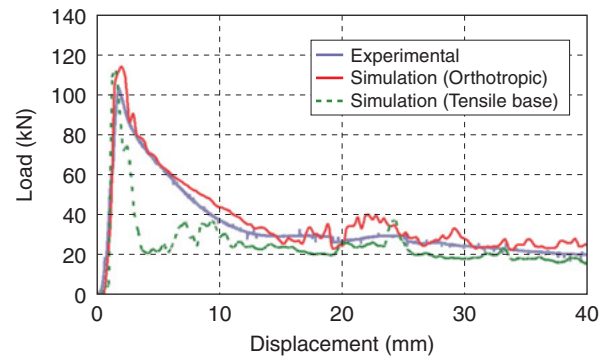


Fig. 24 Load displacement histories of composition A

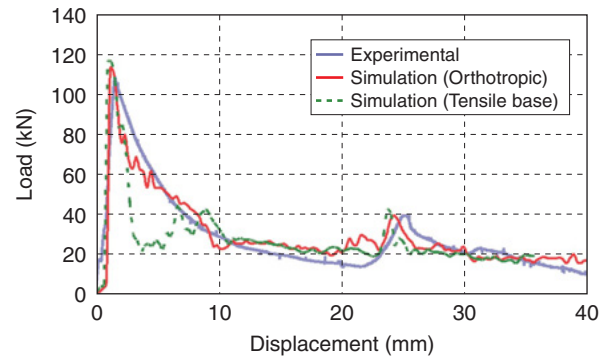


Fig. 25 Load displacement histories of composition B

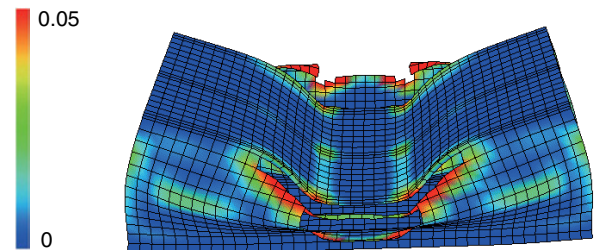


Fig. 26 Equivalent plastic strain distribution of composition A

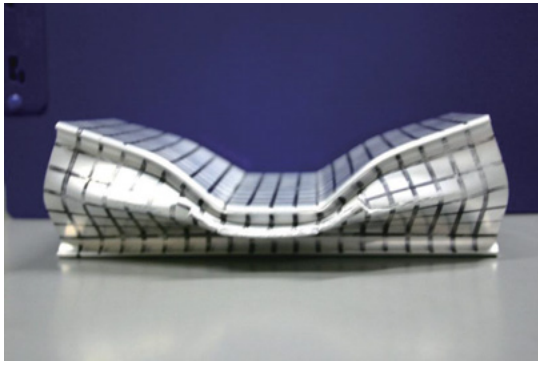


Fig. 27 Photographs of composition A member after crush test

5. Conclusion

A simple orthotropic damage model and simulation method were proposed to predict the crush behavior of extruded aluminum members. This method enables material parameters for the elastoplastic constitutive model to be determined on the basis of the results of tensile tests, and the material parameters for the orthotropic damage model to be determined on the basis of the results of three-point bending tests. Finite element simulations of extruded aluminum member crush tests using these parameters showed correlation with the results of actual tests in terms of load-displacement characteristics and areas in which damage occurred. This suggests that an orthotropic damage model is useful in simulating deformation and load when extruded aluminum members are crushed. The simulation method proposed in this research was shown to be effective in simulating the crush behavior of extruded aluminum members.

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