Development of Material Model for Crack Propagation of Casted Aluminum

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Summary:

This paper describes development of a material model for simulationg crack propagation of casted Aluminum parts.
Authors established a new method for predicting the local fracture strain and strength dependent on solidification time during casting. Also, we introduced another new material model for estimating crack propagation with bi-axial stress distribution. These method and model were applied to a test piece simulation of Aluminum casted parts subject to tensile loads. The crack propagation by FE analysis showed good correlation with that of test. Also, Aluminum sub frame compression test was performed and the crack propagation and force-displacement charcteristics showed a good correlation with that of test.

Keywords:

Computer Aided Engineering(CAE) ,FEM,
Modeling, Crashworthiness /Aluminum ,Material

1 INTRODUCTION

In recent years, Aluminum has been replaced with steel as non-ferrous material for the purpose of lightening of a vehicle and is widely applied to exterior panels and frame structures[1]. Fracture strain of Aluminum is less than steel and an exclusive productive method such as extrusions and casting is available besides panels as a vehicle body structures. Therefore, the modeling technique specialized to Aluminum for the simulation of fracture becomes more necessary in addition to the crash CAE technology which has been mainly focused on steel. Technical development which were implemented so far, as follows.

(1)modeling technique of the thick part of extrusion for crash-box [2]
(2)modeling technique of the arc welding part[3]
(3)prediction of the fracture of a casted B-pillar in the case of a side collision[4]

The damage fracture material model (hereafter, the damage fracture material model is reffered as to The conventional model) is used in the fracture prediction of the B-pillar .

Meanwhile, the Aluminum casted parts such as B-pillar and sub-frame and so on, it is well-known that the material properties of each part depend on the solidification time during casting[5].

If a physical casted part is available and the measurement of the material properties partially could be done, the computational simulation showed better prediction by taking into acount of distributions of yielding stress and so on. However, in the designing step which the physical casted part is not available, it is difficult to consider the distribution of the material properties, because of the lack of measured distributions of yielding stress and so on.

Also, in the case of bending deformation of the B-pillar under the side collision , the conventional material model had enough precision to predict fracture. However, in the case of multiple input-condition of bending and compression of the sub-frame under the front crash collision , the conventional material model did not have enough precision to predict fracture. Therefore,it is necessary to predict more precisely the crack initiation and propagation than the conventional material model .

This paper presents the development of the material model for casted aluminum based on the characteristics discussed above. Then the validation is carried out and the results show the good agreement with the test data.

2 Precision of conventional model

By using the conventional model, the verification of sub-frame under a static compression was executed and the results shows, (1) The crack initiation and propagation positions are different from the test results, (2)force-displacement characteristics is diffrent from the test(Figure 1 and 2). It is thought that the prediction of deformation of the frame in the practical vehicle was difficult due to the insufficient accuracy of the prediction of crack propagation.

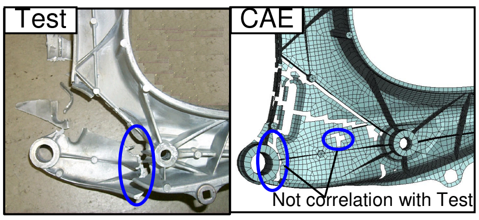

Fig.1 Crack propagation of Sub-frame

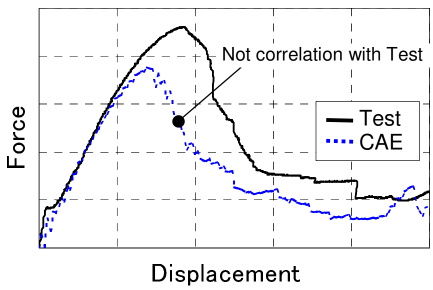

Fig.2 Force-displacement curve of Sub-frame

The authors assumed following hypotheses for the difference of the above-mentioned.

(1)Difference in crack position

Hypothesis 1: The distribution of the material property that originates due to the difference of the solidification time of each part might influence.

(2)Difference of force-displacement characteristics

Hypothesis 2: The rupture order difference might influence the whole progress of the crack development.

Based on the above-mentioned hypotheses, the following measures are planned.
Measures 1: the distribution of the material property by using the casted analysis result (hereafter, call it model with material properties distribution consideration).
Measures 2: The Wilkins model for the crack progergation(hereafter, Wilkins model) is adopted.
That is, a method combining and two models: " model with material properties distribution consideration " and "Wilkins model" is developed.

3 Consideration of material property distribution of Aluminum parts

An original technique (Figure 3) for the material property distribution consideration is developed. First of all, the correlation of the solidification time of existing aluminum parts ((1) in Figure 3) and the material property ((2) in Figure 3)((3) in Figure 3) is taken in STEP1. Next, STEP2, the distribution of the material property is presumed by using the correlation formula ((3) in Figure 3) obtained from the solidification time distribution ((4) in Figure 3) output by the casted simulations of the parts in STEP1, and then converted into a material data ((5) and (6) in Figure 3) for Crash CAE (Hereafter, it is called the mapping).

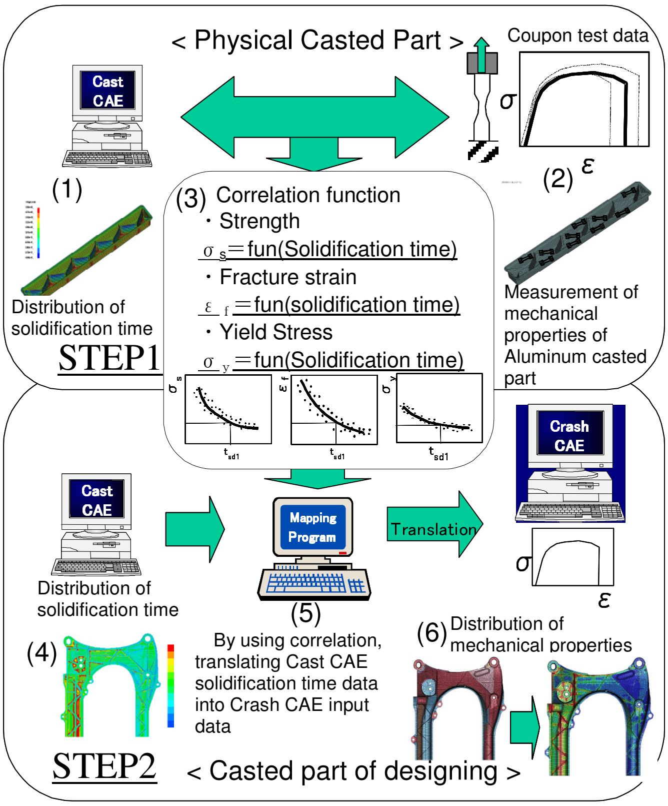

Fig.3 Definition of material *properties*

The details are described as follows.

3.1 Making of correlation formula of solidification time and material properties

When the casted Aluminum parts manufactured, the solidification time is different from thier local position. Then, the solidification time of about 20 different positions has been extracted from the casted simulation results of existing parts. In addition, the material properties are measured for the test pieces cut out at the positions(Figure 4).
The elongation, from the beginning till the necking point, was recorded with the video recorder which is used to obtain true stress-true strain diagram, and data is measured from the images.

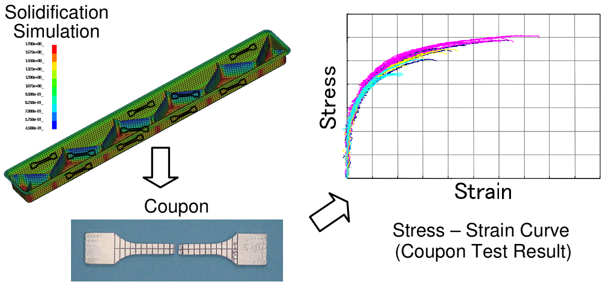

Fig.4 Measurement of material properties

The material properties such as tensile strength, the rupture strain, and yield strength, etc. are extracted from the stress-strain diagram of the test result, and the correlation formula of each properties was decided from the correlation with the solidification time that had been calculated beforehand by the casted simulation. Figure 5 shows the detail correlation formula made from the data of the object of Hat-section shaped specimen and B pillar.

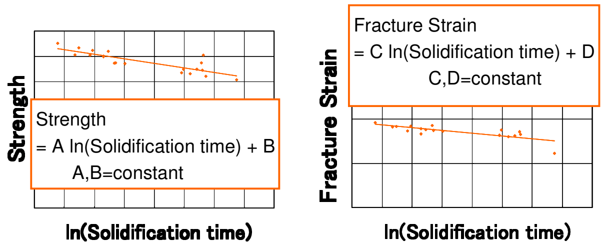

Fig.5 Correlation between properties and solidification time

3.2 Estimation of material property distribution based on solidification time

The casting simulation of a sub-frame was performed, and the distribution of solidification time was obtained. The data is converted into the material property by using the above-mentioned correlation formula, and, in addition, it is converted into material data and input data format for collision CAE (Figure 6).

The mapping algorithm is described in the next paragraph.

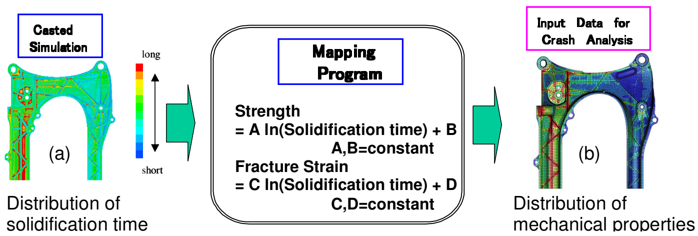

Fig.6 Mapping to input data for crash analysis

3.3 Mapping algorithm

The stress-strain properties is expressed by overlapping the damage function with the undamage properties (compression properties) of the material model used for aluminum so far (Figure 7) [6].

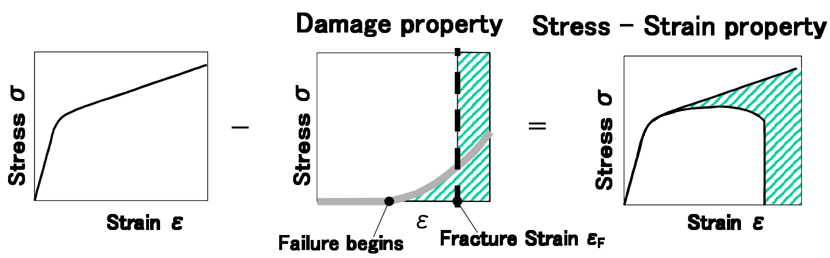

Fig.7 Material model

Then, a standard undamage property was common and damage property was varied with solidification time by using the correlation formula mentioned above. The procedure is described as follows.
First of all, the value of the solidification time and the material property is decided from each correlation formula (Figure 8).

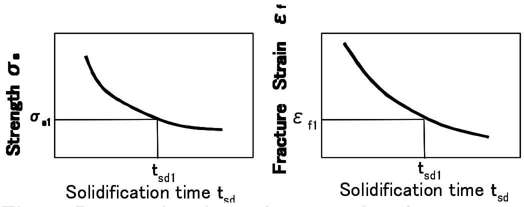

Fig.8 Determination of properties from correlation

Next, a standard undamage property (compression property) is decided from the maximum tensile strength of test data stress-strain properties (Figure 9).

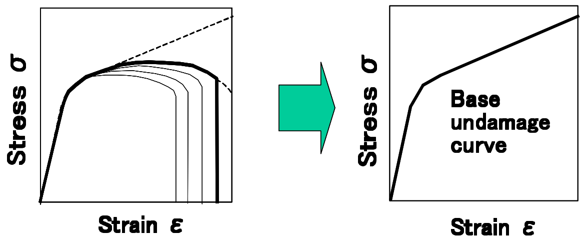

Fig.9 Determination of base undamage curve

Next, the scale factors correlation was made from the ratio of the standard undamage curve to the tested curve of tensile strength, as showed in Figure 10.

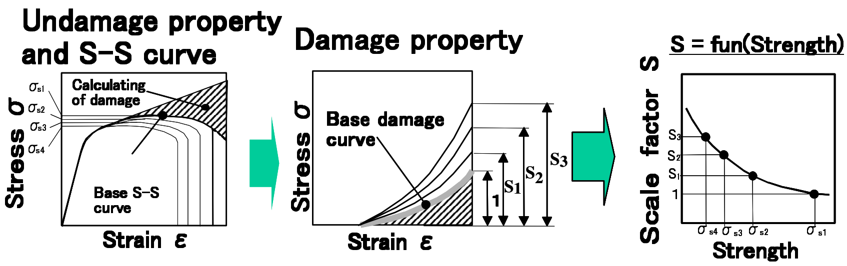

Fig.10 Correlation between Strength and damage

Finally, the stress-strain properties corresponding to each solidification time can be obtained by overlapping the damage properties, which are obtained by multiplying the undamage curve with the scale factor and the rupture strain,respectively (Figure 11).

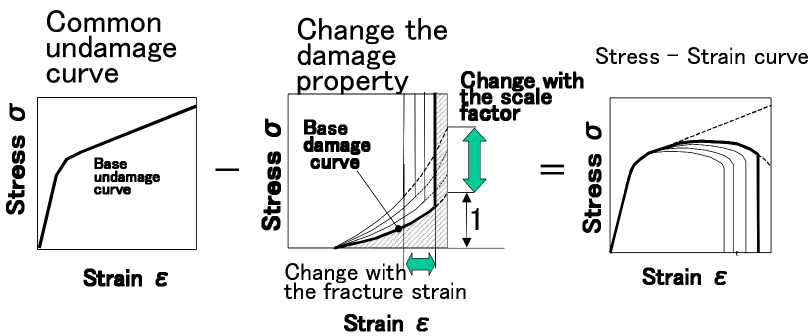

Fig.11 Determination of Stress-strain curve

4 Method for simulating crack propagation

To simulate the propagation of the crack, the Wilkins model is used. This material model is the one in which rupture criteria [7][8] by Wilkins damage D shown in expression (1) was combined with the material model used for the aluminum so far.

$$D = \int \omega_1 \omega_2 d\varepsilon^p \quad \cdots \quad (1)$$

Here, the $\omega 1$ is weight coefficient of hydrostatic pressure, $\omega 2$ is the weight coefficient of the asymmetric component, and ε^p is the equivalent plastic strain. The Wilkins damage, based on the ductility destruction theory proposed by McClintock, that the rupture occurs due to the damage that depends on the strain. As showed in Figure 12, the crack occurs when (1) Wilkins damage D reaches limit damage Dc, (2)the crack propagation is expressed by the change in stress scale F, and (3)the rupture occurs when stress scale F reaches one. An accurate crack forecast is possible for the biaxial stress state because in Wilkins damage model, the rupture judgment depends on the state of the stress which changes through out the process.

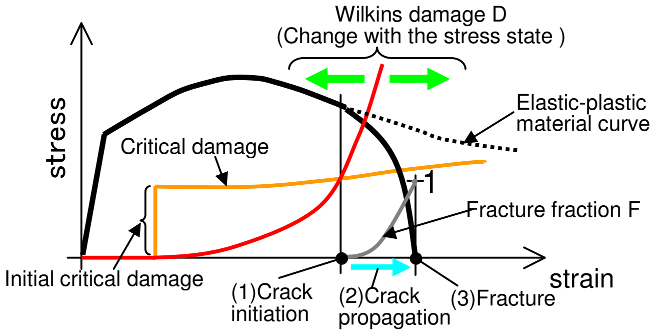

Fig.12 Diagram of fracture propagation material model

5 Verification of test

Using the crack propagation material model proposed above, the new aluminum models(hereafter, call it new model) were made for those objects. The comparison of the model specifications with conventional material models (call it hereafter conventional model) is shown in table 1. No tuning of material property in the model was done, and a uniform material property was used.

The verification is done for this model, and in addition, the verification is also done for sub-frame, which receives a static compression load.

Table.1 Comparison of FE model specification

	Conventional CAE	CAE with New model
Material model	Elastic-plastic material model	Wilkins model
Material property distribution of casted	Not considered	Considered

5.1 Verification of test pieces

Test pieces with various shapes under different tension and bending loads, about 10 cases were verified. Excellent correspondence was obtained by all cases. Here, Table 2 reports the results of the typical 2 cases.

Table.2 Purpose of the validations

		Purpose		
		Force-displacement property	Crack initiation point	Crack propagation
Case1	Bending test of T-section shaped specimen	—	—	○
Case2	Bending test of Hat-section shaped specimen	○	○	—

5.1.1 verifications #1(T-section shaped specimen under three points bending moment)

T-section shaped specimen under three point bending test was performed on the condition, shows in Figure 13, that the rib is layed up wards with the forced displacement at the center part. The force-displacement diagram and deformation are shown in Figure 14 and Figure 15 respectively. It is noted, the rupture timing(A) predicted with the conventional model is earlier than the test data, while the results, like rupture timing (B)and force-displacement curve, predicted with new material model, are very close to the test data. Since the stress concentration of the T-section shaped specimen is a biaxial stress state in nature, and a new model is more accurate for the biaxial stress state.

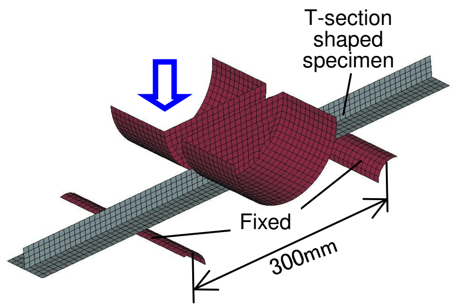

Fig.13 FE model of T-section shaped specimen

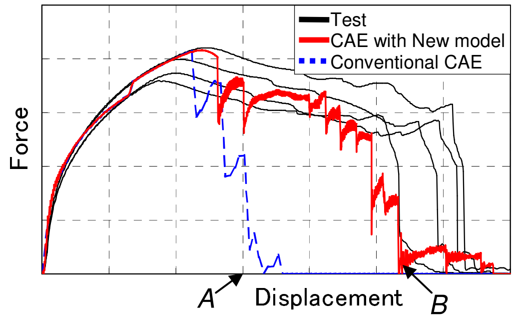

Fig.14 Force-displacement curve of T-section shaped specimen

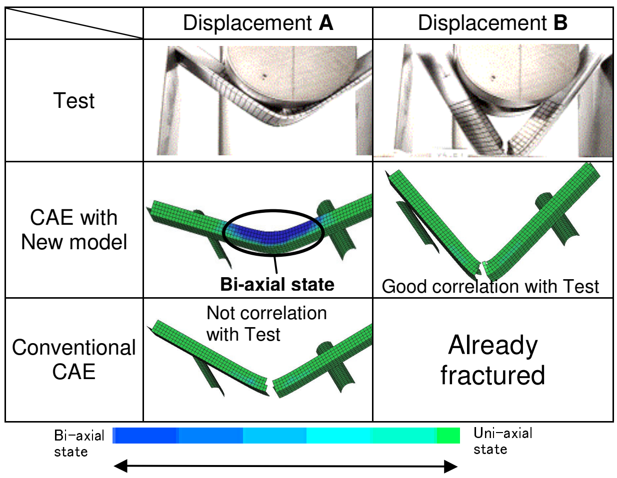

Fig.15 Deformation and Stress state of T-shape specimen

5.1.2 Verifications #2(Hat-section shaped specimen under three points bending moment)

The Hat-section shaped specimen under three point bending test was executed, as showed in Figure 16, on the condition of giving a compulsive displacement to the center part of the Hat-section shaped specimen . The calculated displacement and force-displacement curve are shown in Figure 17 and Figure 18 respectively. Compare with the conventional model, the force-displacement curve, as well as the rupture situation predicted with the new model roughly agreed to the test, while maximum force predicted with the conventional model is high, and no rupture occurs surround the pin.

Because there is a difference in the thickness distribution in the test pieces, and the solidification time is different as shown in the solidification analysis result of Figure 19, the material property is not uniform. In addition, compare with other region, the rupture strain is much smaller around the pin area due to the slower solidification around the pin area. It is thought that the accuracy of the predicted displacement and force-displacement curve can be improved by considering the distribution of the material property, which is typical for such casted process, in the new model.

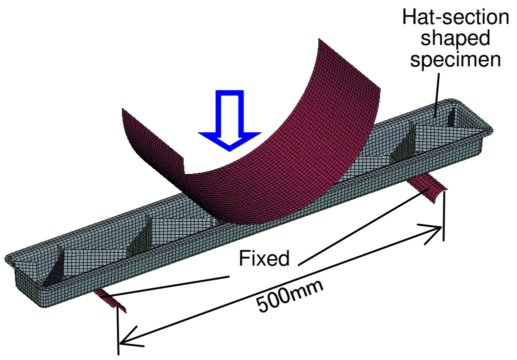

Fig.16 FE model of Hat-section shaped specimen

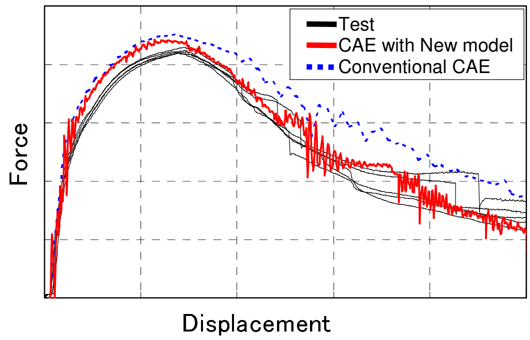

Fig.17 Force-displacement curve of Hat-section shaped specimen

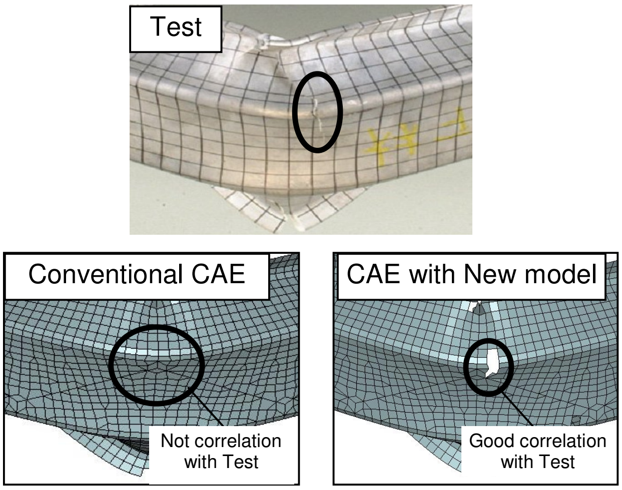

Fig.18 Crack propagation of Hat-section shaped specimen

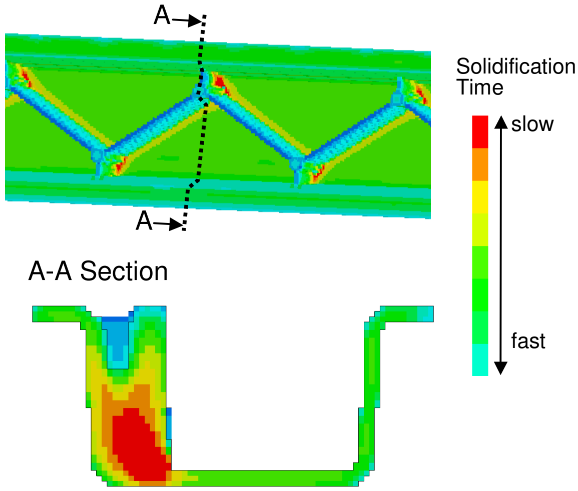

Fig.19 Solidification time distribution of Hat-section shaped specimen

5.2 Verification of sub-frame compression test

As showed in Figure 20, to obtain offset collision results, the sub-frame was set inclined up on the condition of giving the compulsion displacement to one of the connecting point with the vehicle. The force-displacement curve and the deformation are shown in Figure 21 and Figure 22 respectively. Compare with the tested data, the predicted maximum load is lower and the rupture region with the conventional model is different, while using new model the predicted results roughly agrees with the tested results. Especially, the new model improves the rupture prediction in region A, where rupture predicted as the test results, and this can not been seen with conventional model. As for this, the solidification of region A is early, and the rupture strain large and this effect has been taken into consideration in the new model. Moreover, the state of the stress and the rupture situation in the time series are compared with conventional model to investigate the rupture timing of the stress concentration region, as shown in Figure 23. The stress concentration part is a biaxial stress state, the same as T shaped specimen under three point bending test, and it confirmed that the rupture timing predicted with conventional model is earlier.

For purpose of investigating the rupture strain under biaxial stress state, 3 cases of biaxial tension calculation was performed. In conventional model, the maximum principal strain at rupture time keeps unchanged even while change the stress state. But with Wilkins models, the rupture strain changes accordingly. This can be explained as those Wilkins model responses well with the formation of boundary limit so that it can give a good accuracy in biaxial stress state. That's why it enhanced accuracy in predicting the rupture of sub-frame.

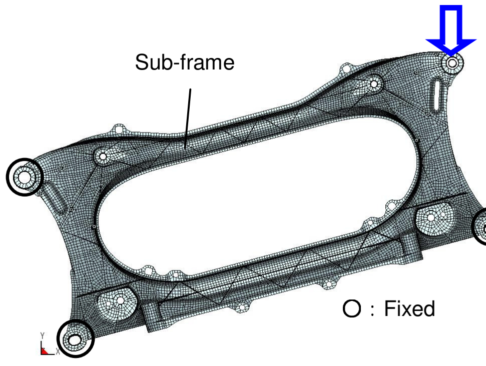

Fig.20 FE model of Sub-frame

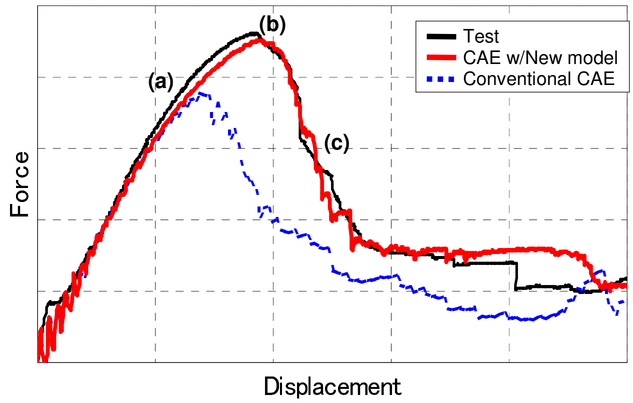

Fig.21 Force-displacement curve of Sub-frame

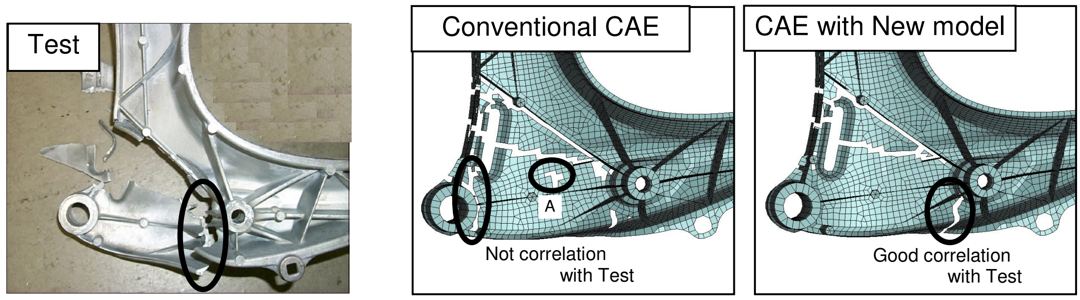

Fig.22 Crack propagation of Sub-frame

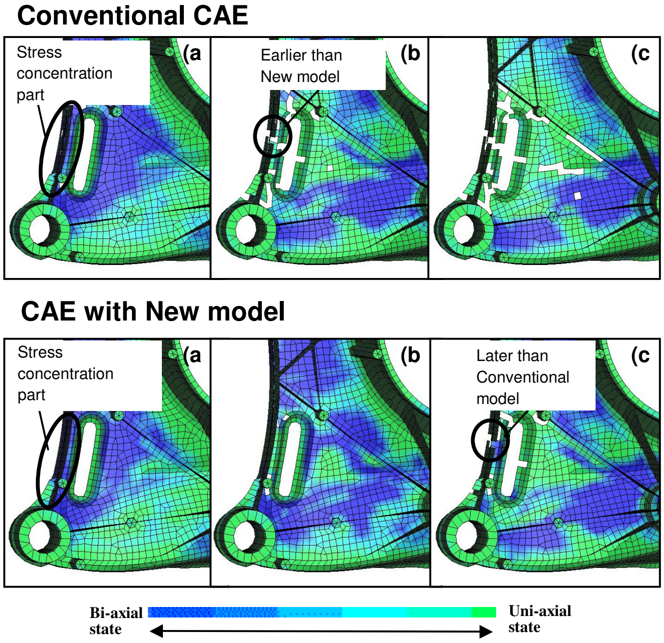

Fig.23 Stress state and Crack condition of Sub-frame

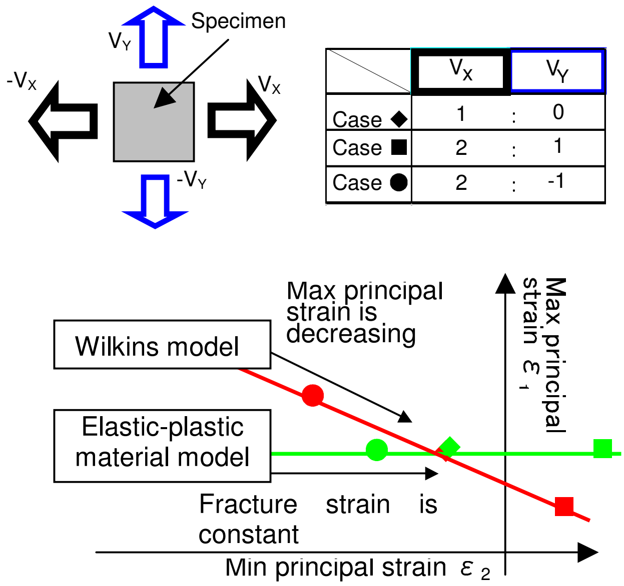

Fig.24 Bi-axial tensile simulation

6 Conclusions

The authors developed the method for casted Aluminum parts combining the Wilkins damage model and consideration of material property distribution. By using this method, the crack propagation and force-displacement characteristics were more accurately predicted. The verification confirmed that not only drawing information but also the material property distribution that originated from the solidification time in the manufacturing process are important factors in predicting the crack propagation.

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