

Simulation of Adhesively Bonded Parts for Multi-Material Bonding Structure

Tomohiro SHIMAMIYA*

Chiaki SATO**

Eiichiro YOKOI*

Toru FURUSAWA*

Keiichi SATO*

ABSTRACT

In order to perform completed vehicle crash simulations involving the destruction of adhesively bonded parts, a damage mechanics model called a cohesive zone model was applied to the adhesively bonded parts. A dynamic tension-torsion testing method that supports a wide range of strain rates was constructed to take into account the strain rate dependency.

Simulations using cohesive zone model of adhesively bonded parts were performed at levels ranging from the small-scale coupon level to completed vehicle crash simulations. These results were compared with the results of full structure destruction behavior tests and exhibited a good correlation.

1. Introduction

CO₂ emission standards for automobiles are becoming more stringent year by year. Reduction of vehicle body traveling energy by reducing the body weight is an effective method of reducing CO₂ emissions. One measure for achieving this is the replacement of conventionally used steel with other materials, and further body weight reduction is anticipated as bodies become increasingly multi-material through the use in appropriate locations of materials such as nonferrous metals and glass fiber-reinforced plastic that have good specific rigidity, and carbon fiber-reinforced plastic that also has good specific strength.

The issue in these cases is the method used to bond the different materials in place of steel joining methods such as spot welding, and the most promising of these methods is currently adhesive bonding.

Adhesive bonding has been used thus far for applications such as attaching the windshield. When limited to the range lower than the adhesive strength, the degree of contribution of adhesively bonded parts in body design can be predicted by static simulation using a continuum mechanics model. However, when performing simulations that involve the destruction of adhesively bonded parts, it is necessary to first determine the crack initiation position using a continuum mechanics model, and then apply a fracture mechanics model to express the crack propagation from that point⁽¹⁾. For this reason, the calculation costs increase due to

the calculations needed to couple both models. In addition, the resin materials that are the main components of the adhesive generally have a high strain rate dependency, so the strain rate produced on adhesively bonded parts also needs to be taken into account in order to perform crash simulations that include adhesively bonded parts.

One model that deals with crack propagation is the virtual crack closure technique (VCCT)⁽²⁾, but this method has two major issues. One is that special elements need to be located beforehand in the crack initiation positions; that is to say it is necessary to use some method such as stress analysis to determine the positions where cracks may occur in advance. The other issue is that the analysis time increases due to the need to recreate the analysis mesh in order to determine the path in accordance with crack propagation⁽³⁾.

Increasing the accuracy of completed vehicle crash simulations helps to avoid reworking due to failure to achieve requirements during actual crash tests, and is essential for efficient vehicle development. This study used a damage mechanics model to express the progression from crack initiation to breaking within the continuum mechanics framework. Specifically, a cohesive zone model (CZM) was used as the damage mechanics model applied to the adhesively bonded parts. In addition, a testing method for acquiring material properties was constructed that also supports strain rates that cannot be covered by conventional testing standards, and verification was performed by

* Automobile R&D Center

** Tokyo Institute of Technology

comparing simulations ranging from the small-scale coupon level to completed vehicle crash simulations with the results of destruction behavior tests to confirm the usefulness of the developed method.

2. CZM and Material Parameters

A CZM is a damage mechanics model that has energy as an input parameter and uses damage to express the drop in rigidity. This enables handling of the entire progression from crack initiation to propagation and breaking as a single process within the continuum mechanics framework⁽⁴⁾. Figure 1 shows an example of typical definitions of CZM material parameters.

This study used definitions of CZM material parameters that express the relationship between deformation and stress with a triangle. The initial gradient K in the figure represents the modulus of elasticity of the adhesive divided by the adhesive thickness, the peak height σ represents the crack initiation stress, and the triangle area G_c represents the energy absorbed per unit area until the crack breaks. This is called the energy release rate. These definitions enable expression of the series of phenomena until adhesively bonded parts break. That is to say, elastic behavior is exhibited until the stress applied to the adhesively bonded parts exceeds σ , crack initiation occurs when the stress reaches σ , and then the stress decreases in a linear manner due to a drop in rigidity as cracking propagates, and breaking ultimately occurs at the point when the stress reaches zero.

Figure 2 shows the types of crack propagation mode handled by CZM.

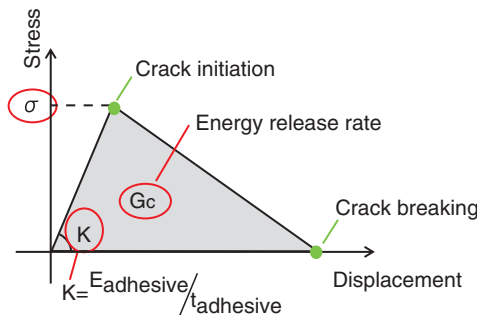


Fig. 1 Example of CZM parameter definition

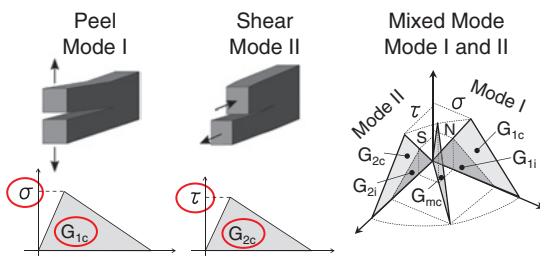


Fig. 2 Types of crack mode

The CZM material parameters are defined separately for Mode I: Peel and Mode II: Shear. In addition, in the case of a peel phenomenon where Modes I and II are mixed and apply in a compound manner (Mixed Mode), the crack initiation stress is defined using Eq. (1), and the energy release rate is defined using Eq. (2)⁽⁵⁾.

$$\left(\frac{N}{\sigma}\right)^2 + \left(\frac{S}{\tau}\right)^2 = 1 \quad (1)$$

$$G_{1C} + (G_{2C} - G_{1C}) * \left(\frac{G_{2i}}{G_{1i} + G_{2i}}\right)^\eta = G_{mc} \quad (2)$$

The advantage of using CZM to model adhesively bonded parts is that the crack initiation and propagation calculations do not require a detailed stress distribution in the adhesive layer thickness direction, so detailed element division and calculations in the thickness direction are unnecessary, which helps to suppress expansion of the analysis model scale. In addition, the time step determined from the minimum element length in the explicit analysis code does not need to be reduced, enabling reduction of crash simulation costs.

3. Material Property Tests

3.1. Quasi-static Material Property Tests

Table 1 shows the test standards for the three modes described in section 2⁽⁶⁾⁻⁽¹⁰⁾. The subject of all the standards is quasi-static tests, and the adhesive bonding standard is only for Mode I: Peel, however interlaminar standards for composite material laminated plates were also referenced.

In all of the above test standards, a force-stroke diagram can be obtained as a result of applying a load to a test piece consisting of two plates joined by adhesive as shown in Fig. 3. A description of the test, the test setup and the obtained force-stroke diagram for each mode are given below.

Figure 4 and Fig. 5 show the Double Cantilever Beam (DCB) test that corresponds to Mode I. The DCB test applies a tensile load to the adhesively bonded parts by applying a vertical load to the test piece via a universal joint.

Figure 6 and Fig. 7 show the End-Notched Flexure (ENF) test that corresponds to Mode II. The ENF test applies a shear load to the adhesively bonded parts by applying 3-point bending directly to the test piece.

Figure 8 and Fig. 9 show the Mixed Mode Bending (MMB) test. The MMB test is able to simultaneously apply both Mode I: Peel and Mode II: Shear to the adhesively bonded parts, and the ratio of peel and shear can be arbitrarily changed by adjusting the arm length c .

3.2. Dynamic Material Property Tests

A dynamic testing method for acquiring material properties was constructed to understand the strain rate dependency. Figure 10 shows an outline of the test method.

Table 1 Test standards for CZM parameters

Standard		Mode I Peel	Mode II Shear	Mode I and II Mixed Mode
Adhesive	ASTM	D3433-99(2012)	-	-
	JIS	K 7086	K 7086	-
FRP Interlaminar	ASTM	D5528-13	D7905M-14	D6671M-13e1
	JIS	K 7086	K 7086	-

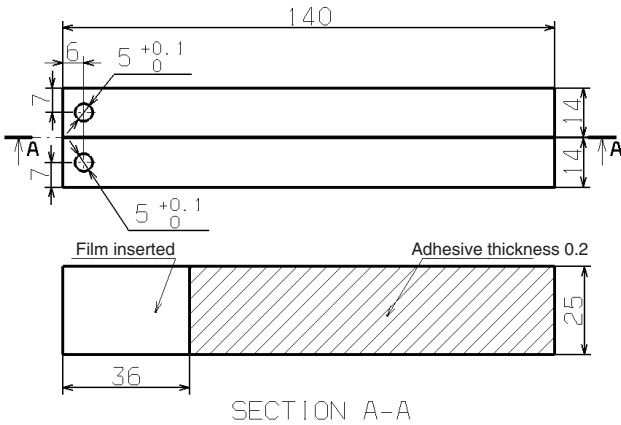


Fig. 3 Test piece drawing

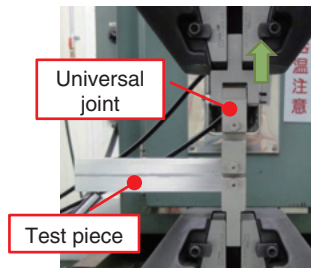


Fig. 4 DCB test setup

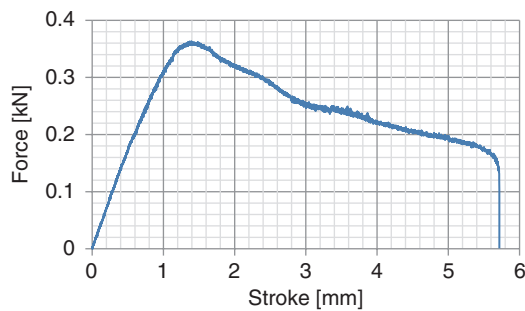


Fig. 5 Force-stroke diagram of DCB test

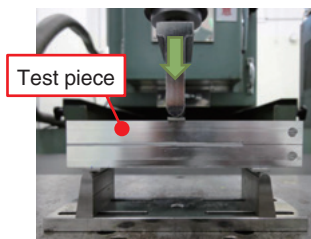


Fig. 6 ENF test setup

This method enables performance of tests for Mode I only and Mode II only as well as the intermediate Mixed Mode with a single apparatus by applying tensile and torsional loads in the arbitrary ratios to a cylindrical test piece joined by adhesive, and also supports high strain rates by increasing the loading rate.

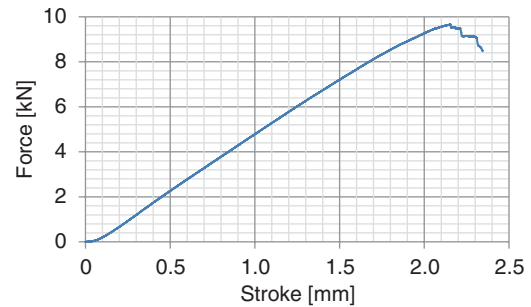


Fig. 7 Force-stroke diagram of ENF test

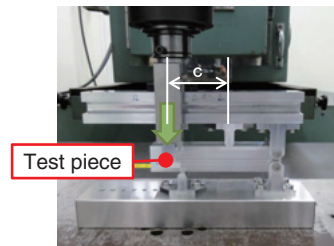


Fig. 8 MMB test setup

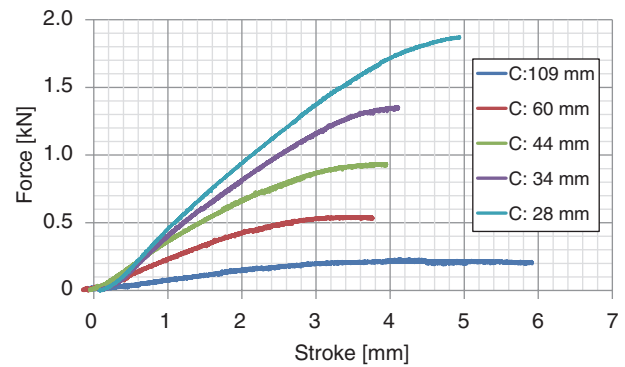


Fig. 9 Force-stroke diagrams of MMB test

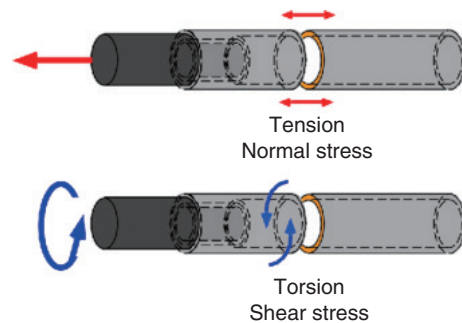


Fig. 10 Concept of loading

Figure 11 shows the overall testing machine. The start timing of the tensile and torsional loads applied to the test piece can be aligned by applying hydraulic pressure supplied from a pump to the drive pistons via two systems of servo valves⁽¹¹⁾.

Gap sensors that obtain the displacement in the axial and circumferential directions are installed around the test piece set inside the chamber at the top of the testing machine as shown in Fig. 12, and the stress-displacement diagram for each mode can be obtained by combining the load cell value. Figure 13 shows an example of the obtained stress-

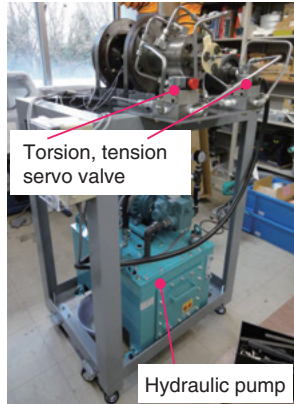


Fig. 11 Dynamic tension-torsion testing machine

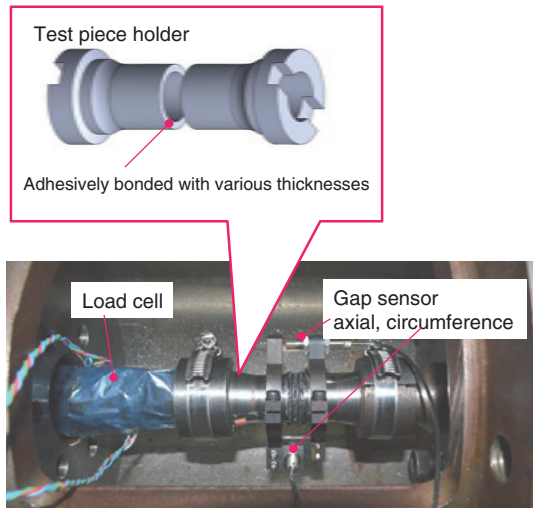


Fig. 12 Setup of test piece

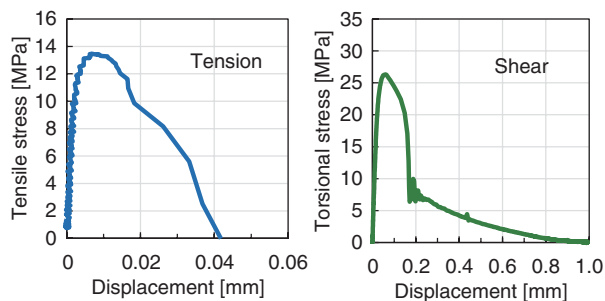


Fig. 13 Stress-displacement diagrams

displacement diagrams, and Fig. 14 shows the relationship between the tensile stress and torsional stress in Mixed Mode.

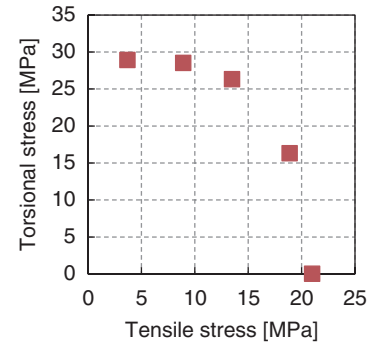


Fig. 14 Tensile-torsional stress diagram

4. Identification of CZM Material Parameters

The test standards noted in Table 1 include methods for directly calculating the energy release rate from the force-stroke diagram obtained by the tests. However, this study adopted the following method for identifying the parameters. First, an analysis model was created with the same test pieces, constraints and loading conditions as those in the material property tests, and then the CZM material parameters were repeatedly adjusted until the force-stroke diagrams obtained by analysis and the tests match.

4.1. Identification of Quasi-static CZM Material Parameters

Regarding the quasi-static CZM material parameters, the Mode I CZM material parameters are identified from the DCB test results, the Mode II CZM material parameters are identified from the ENF test results, and η in Eq. (2) is identified from the MMB test results. Figure 15 shows an example of the CZM material parameters identified for two adhesives.

The adhesives shown here are both acrylic adhesives, but when expressed by the CZM material parameters, the size and balance of the respective triangles differ greatly.

4.2. Identification of Dynamic CZM Material Parameters

Regarding the dynamic CZM material parameters, an

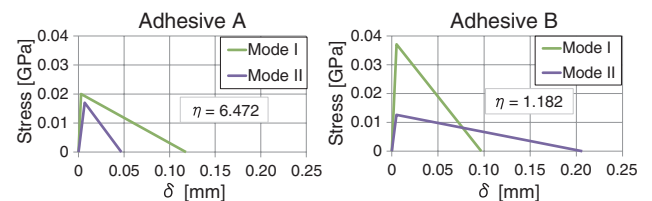


Fig. 15 Two examples of identified quasi-static CZM parameters

analysis model equivalent to the dynamic tension-torsion test was created, and the Mode I and Mode II CZM material parameters and η were all three identified simultaneously from the analysis results. Figure 16 shows the identified CZM material parameters of adhesive A.

This shows that the dynamic CZM material parameters for Mode II in particular differ greatly from the previously identified quasi-static CZM parameters.

The energy release rate is influenced by the element size, so if the element length in the in-plane direction of the adhesive bonding surface differs, the analysis results will differ even when using the same CZM material parameters. Therefore, the element length was standardized within the same analysis model or between different analysis models when modeling adhesively bonded parts.

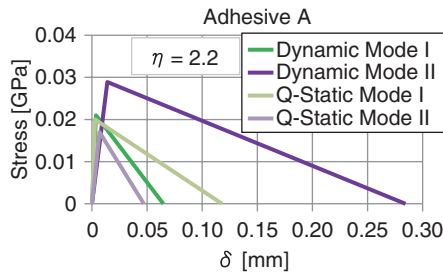


Fig. 16 Example of identified dynamic CZM parameters

5. Confirmation of Usefulness

The usefulness of the adhesive bonding part simulation method using CZM was confirmed by comparative verification with tests at five different levels. The items used to confirm usefulness at each level are as follows.

- Coupon level: quasi-static CZM material parameters
- Element level: dynamic CZM material parameters
- Subcomponent level: dynamic destruction behavior of bonded parts
- Component level: overall behavior of medium-scale structure
- Completed vehicle level: overall behavior of full vehicle

The comparison results at each level are described below.

5.1. Coupon Level: Single Lap Shear Test

The single lap shear test is a quasi-static test that obtains the typical tensile shear strength; that is to say the value obtained by dividing the fracture load of the adhesively bonded parts by the bonded area. Figure 17 shows an outline of the single lap shear test piece.

Single lap shear tests⁽¹²⁾ were performed using adhesives A and B with the three different lap lengths of 12.5 mm, 25 mm and 50 mm to confirm the usefulness of the quasi-static CZM material parameters identified in section 4.1. Figure 18 compares the test and analysis results.

Comparison of the tensile shear strength test results (the blue plots in the figure) for lap lengths of 12.5 mm and 50 mm shows that while the tensile shear strength of adhesive A changed by only a small amount from 8.6 MPa to 8.0 MPa, the tensile shear strength of adhesive B dropped from 10.5 MPa to 6.0 MPa.

In addition, analysis that uses CZM (the red plots in the figure) expresses the degree of change in the tensile shear strength relative to the lap length, and the analysis results matched closely with the test results in all cases.

The above results confirmed that CZM material parameters are useful at the coupon test level for predicting the strength of adhesively bonded parts with various lap lengths.

5.2. Element Level: HAT 3-point Bending Test

A dynamic HAT 3-point bending test using a falling weight testing machine was performed to confirm the usefulness of the dynamic CZM material parameters identified in section 4.2. Figure 19 shows an outline of the test. The test piece consisted of a HAT section component and a flat plate molded out of carbon fiber-reinforced thermoplastic (CFRTP) resin and adhesively bonded in the flange parts. Bonding used adhesive A and analysis used the dynamic CZM material parameters identified in section 4.2.

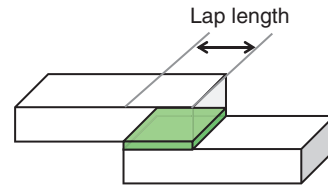


Fig. 17 Test piece for single lap shear test

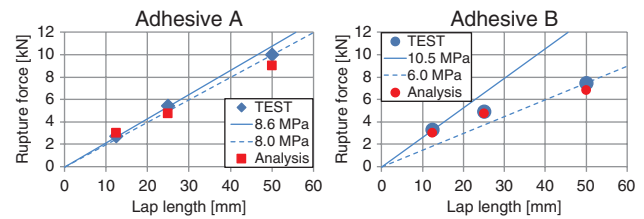


Fig. 18 Rupture force vs. lap length

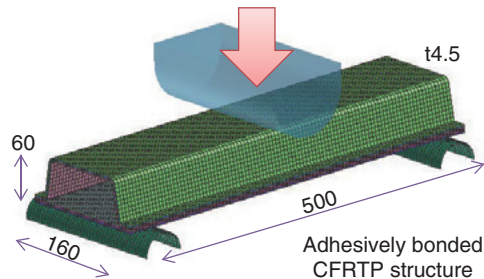


Fig. 19 HAT 3-point bending

Figure 20 compares the test piece destruction formats in the test and the analysis, and Fig. 21 compares the obtained force-stroke diagrams.

The comparison in Fig. 20 shows that the analysis is also able to express the destruction sequence whereby the adhesive in the flange parts peels as the load is applied, with the result that the HAT component and the flat plate are separated, the HAT component fractures, and the flat plate experiences elastic deformation. In addition, the comparison of force-stroke diagrams in Fig. 21 shows that the analysis error at the initial peak force is approximately 10%, and the analysis also closely reproduces the change in force in accordance with the destruction sequence.

The above results confirmed that dynamic CZM material parameters are useful for analysis at the element level that includes the destruction of simple adhesively bonded parts.

5.3. Subcomponent Level: T-Joint Test

A dynamic T-Joint test using a falling weight testing machine was performed to confirm usefulness at the subcomponent level. Figure 22 shows an outline of the test piece. Aluminum HAT components and flat plates adhesively bonded in the flange parts were further

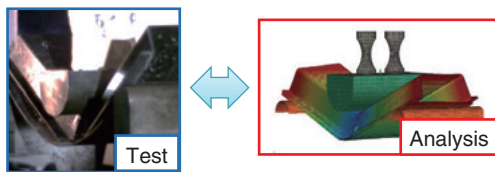


Fig. 20 Comparison of test piece destruction

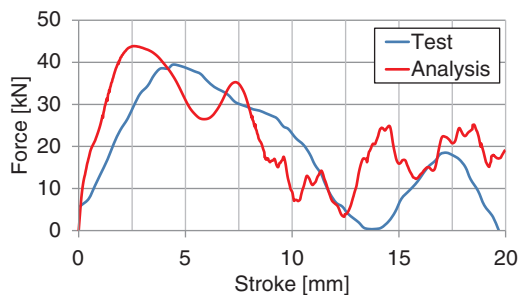


Fig. 21 Comparison of force-stroke diagrams

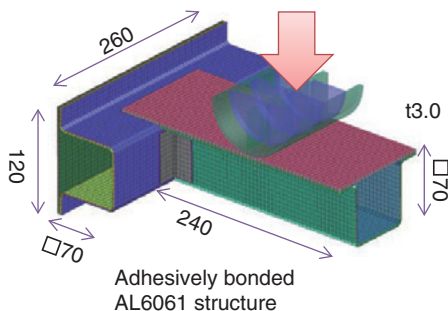


Fig. 22 T-joint test piece

assembled into a “T” shape, and the intersecting parts were adhesively bonded using L clips. This means that the adhesively bonded surfaces are located in various directions relative to the loading direction. Bonding used adhesive A and analysis used the dynamic CZM material parameters identified in section 4.2. Figure 23 compares the test piece destruction aspects, and Fig. 24 compares the obtained force-stroke diagrams.

The comparison in Fig. 23 shows that the analysis is also able to express the dynamic destruction sequence, whereby destruction of the adhesively bonded parts started from the tip and propagates toward the base of the test piece. In addition, the comparison of force-stroke diagrams in Fig. 24 shows that the analysis error at the initial peak force is within 10%, and the analysis also closely reproduces the change in force in accordance with the destruction sequence.

The above results confirmed that CZM material parameters are also useful for analysis at the subcomponent level that includes the destruction of complex adhesively bonded parts.

5.4. Component Level: Floor Side Sill Test

A floor side sill test was performed to confirm usefulness at the component level. The floor side sill component used as the test piece consisted of multiple parts joined by adhesive bonding. This test was a quasi-static load test that simulates collision with a pole, and the results were compared with those of a corresponding analysis model. Figure 25 compares the destruction aspects, and Fig. 26 compares the obtained force-stroke diagrams.

The test results in Fig. 25 show that buckling occurred in the floor plate due to adhesive layer peeling of the floor part, and the resulting drop in the floor part yield strength led to increased bending in the side sill parts and destruction

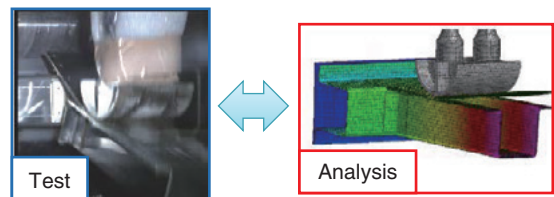


Fig. 23 Comparison of test piece destruction

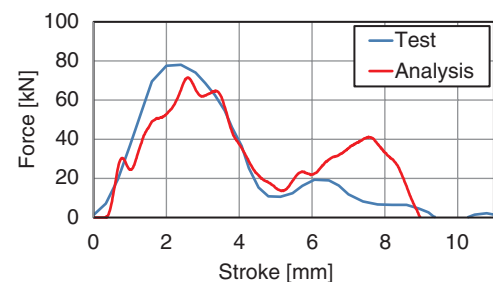


Fig. 24 Comparison of force-stroke diagrams

directly below the indenter. The analysis results accurately reproduced this destruction sequence, and the deformation accompanying the destruction also closely matched the test results. In addition, the force-stroke diagram in Fig. 26 shows that during the test, the force dropped sharply when the floor part yield strength dropped due to adhesive layer peeling, and residual strength was maintained thereafter due to side sill bending. In contrast, in the analysis results when rigid body coupling is applied and adhesively bonded part destruction does not occur (Analysis_RIGID), the floor part adhesive layer does not peel, so there is no drop in the floor part yield strength and the force continues to increase, behavior that completely differs from the test results. On the other hand, the analysis results when CZM are applied to adhesively bonded parts (Analysis_CZM) reproduce the drop in force due to the drop in floor part yield strength, and the residual strength thereafter also closely matches that of the test results. This indicates that the new analysis method accurately modeled the parts that experienced actual destruction, and that expressing this destruction at the appropriate timing accurately reproduces the behavior of the full structure.

The above results confirmed that CZM material parameters are also useful for component level analysis in which the destructive behavior of the full structure may change greatly depending on whether destruction of adhesively bonded parts occurs.

5.5. Completed Vehicle Level: SINCAP Test

A Side Impact New Car Assessment Program (SINCAP) test was performed using a body that includes adhesively bonded parts to confirm usefulness at the completed vehicle level. While the details of the body used and the test contents are omitted here, Fig. 27 compares the obtained force diagrams.

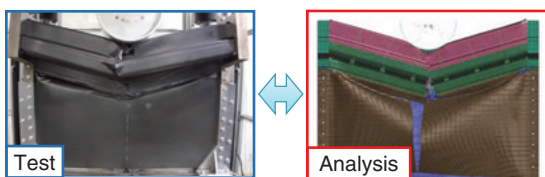


Fig. 25 Comparison of test piece destruction

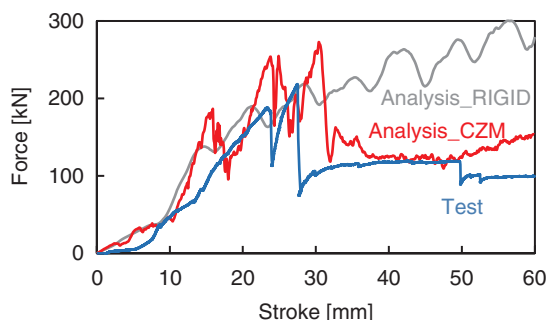


Fig. 26 Comparison of force-stroke diagrams

Compared to the analysis results when rigid body coupling is applied and adhesively bonded part destruction does not occur (Analysis_RIGID), the analysis results when CZM are applied to adhesively bonded parts (Analysis_CZM) accurately reproduced the behavior of the full vehicle including the destruction sequence, which increased the accuracy of the force diagram.

The above results confirmed that CZM material parameters are also useful for large-scale vehicle crash simulations in which destruction of adhesively bonded parts and other destruction phenomena are complexly intertwined.

The results introduced in this paper confirmed the usefulness of this simulation method using CZM from the small-scale coupon level to large-scale vehicle crash simulations.

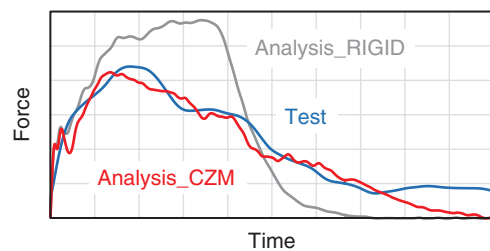


Fig. 27 Comparison of force diagrams

6. Conclusion

Crash simulations using CZM for adhesively bonded parts were performed based on the approach of using a damage mechanics model in the continuum mechanics calculation method. A method was created for acquiring dynamic material properties using a tension-torsion testing machine, and a process was constructed for identifying CZM material parameters from the property test results and executing analysis.

The usefulness of this method was confirmed from the small-scale element level to large-scale vehicle crash simulations. The use of CZM that simulate the entire progression from crack initiation to propagation and breaking as a single process enhanced the reproducibility of full structure behavior that involves the destruction of adhesively bonded parts and obtained good analysis results at all levels.

These results showed that this method is useful for crash simulations at all levels that include adhesive bonding, and particularly for large-scale analyses such as vehicle crash simulations.

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■ Author ■



Tomohiro SHIMAMIYA



Chiaki SATO



Eiichiro YOKOI



Toru FURUSAWA



Keiichi SATO