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Shear directional impact characteristics of adhesively bonded tubular joints

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The adhesive joint is able to reduce the weight of automobiles compared with mechanical joining and withstand stress concentration on the joint parts. Moreover, it can prevent chemical corrosion, which occurs in the bonding between heterogeneous materials. However, the application of structural adhesives on the automotive structures is limited since the basic characteristics of adhesive joints, such as crashworthiness, fatigue and environmental robustness, are not sufficiently revealed yet. Also, shear characteristics of adhesive joints are crucial because adhesive joints are normally applied to structures, which are exposed to shear loading. Therefore, in the present study, impact test and computer simulation were performed to investigate the shear impact characteristics of adhesively bonded joints.

Keywords: structural adhesives; impact test; impact analysis; shear impact characteristics

1. Introduction

A spot welding is mainly used in automotive structures as one of the joining methods. However, nonferrous metals and nonmetallic materials are gradually applied to auto-body for the lightweight effect; therefore, joinings between ferrous and nonferrous metals or metals and nonmetals are demanded nowadays. One of the best candidates for joining methods between heterogeneous materials is the adhesive bonding. It enables us to mitigate noise/vibration and prevent automotive structures from stress concentration and galvanic corrosion. Depending upon the location of bonding spots, it is possible to improve structural stiffness of an auto-body. Apart from these benefits, it is also helpful to reduce weights compared to mechanical joining. Moreover, it is known that adhesives have excellent effect on the fatigue characteristics of structures.[1] However, the application of adhesives on automotive structures is limited since the basic characteristics of adhesive joints, such as crashworthiness, fatigue and environmental robustness, are not sufficiently revealed yet.[2] Cariberger and Stigh [3] suggested an explicit FE model of impact fracture for an adhesive joint. Goglio and Rossetto [4] performed impact rupture of structural adhesive joints under different stress combinations. Arenas et al. [5] proposed a statistical techniques using Weibull distribution for finding

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optimum thickness of single lap adhesive joints. Yang et al. [6] modelled high-strength steel joints using toughened adhesives in vehicle crash simulation. Liao et al. [7,8] performed three-dimensional FE analysis and experiment to investigate the behaviour of single-lap adhesive joints subjected to impact tensile loading. Wu et al. [9] investigated the transverse directional crashworthiness of CFRP adhesively bonded joints experimentally.

Also, shear characteristics of adhesive joints are crucial because adhesive joints are normally applied to structures, which are exposed to shear loading. As mentioned above, it was hard to find topics related to the shear impact characteristics of adhesive joints; therefore, in the present study, impact test and computer simulation were performed to investigate the shear impact characteristics of adhesively bonded joints. For impact tests, an instrumented drop-type impact tester (Instron Dynatup 9250 HV) was used with the newly designed shear-type impact specimen in the present study. LS-DYNA Ver. 971(Livermore Software Technology Co.) was used for computer simulation of impact phenomena.

2. Preparation of the shear impact test for adhesive joints

As the representative standard for the impact test for the adhesives, ASTM D950-03 did not match well with an instrumented drop-type tester; therefore, a modified adhesive joint specimen, based on Bezemer et al. [10,11], was newly proposed in this study as shown in Figure 1.

A decent thickness for the adhesive layer, i.e. distance between inner and outer adherents, was recommended around 0.1–1.0 mm.[5,12,13] Therefore, the thickness of the adhesive layer in the new impact specimen was set to be 0.5 mm. Meanwhile, the adhesion area was considered as 50% of the adhesion area specified in ASTM D950-03 considering the maximum allowable load and safety based on the static test results.[8] Carbon steel AISI 1045 was used for the mechanical structure of adherend pins and rings. The surface of the pin and ring on which adhesive was applied was treated with a #80 sandpaper so that the mean roughness (*Ra*) of the surface would be 1.5 μm [11,12], since the failure of adhesives is affected by the surface roughness of a specimen.[1,12] By the way, the mean surface roughness (*Ra*) was checked using a

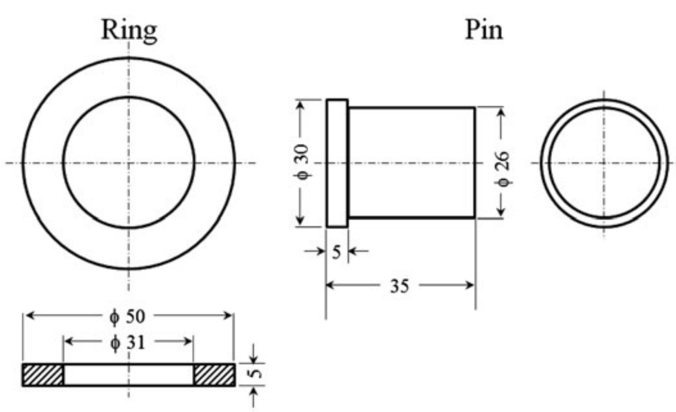


Figure 1. The shape and size of the impact test specimen.

contact-type surface roughness measuring profiler (Surtronic 25, Taylor Hobson Ltd). The pin and ring were then immersed in acetone for around 20 min to remove the impurities sticking to the surface. After completing surface treatment in the pin and ring, an adhesive was applied on the adherends. For adhesive, a structural C-type epoxy adhesive from UNITECH Co. Ltd. [14] was used. The pin and ring were placed on a V-block to align each centre by fixing them using a U clamp, as shown in Figure 2. The fixed adhesive specimen on the V-block was then cured inside the furnace at 180 °C for longer than 20 min in accordance with the adhesive manufacturer's recommendation.[14]

Figure 3 shows the experimental set-up for the newly designed shear impact test specimen. Instrumented impact tester Instron Dynatup 9250 HV (Instron Co. Ltd) was used for the test. Data were stored in the PC after processing with an AD converter (NI Instrument Co. Ltd). Incident speeds of the striker was set to be 4 and 5 m/s to investigate the shear characteristics of an adhesive at low and medium strain rates, which

(a)

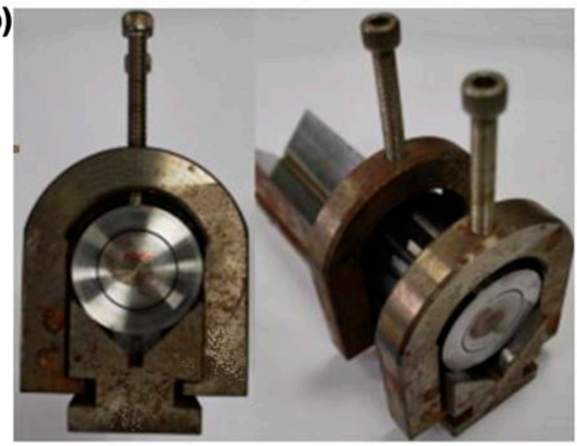
(b)


Figure 2. Specimen preparation. (a) Measurement of the surface roughness and (b) V-block for aligning adherends.

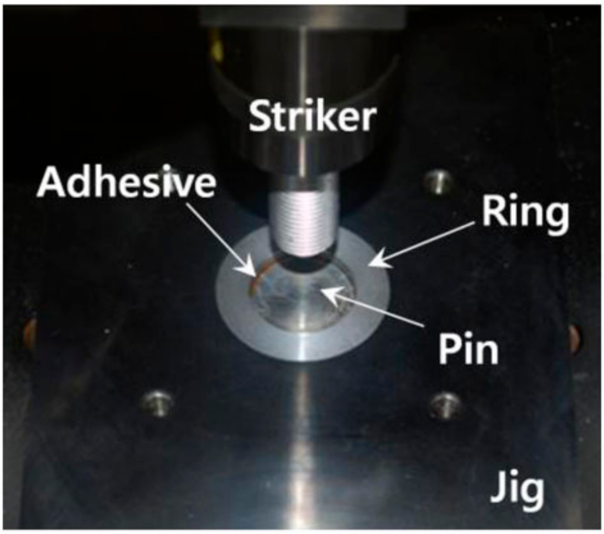


Figure 3. Experimental set-up.

Table 1. Specifications of the shear impact test.

Specification	
Adhesive	Epoxy (Unitech C-type)
Surface cleaner	Aceton
Curing temperature (°C) and duration (min)	180, 20
Adherend	AISI 1045
Surface roughness, *Ra* (μm)	1.5
Incident speed (m/s)	4, 5
Striker mass (kg)	20
Environment temperature (°C)	20 ± 3
Number of specimens	4

cover most cases of vehicle crash.[15–17] The striker mass was set to be 20 kg. Detailed description of the shear impact test is summarized in Table 1.

3. Finite element analysis of adhesive joints

Shear impact failure of adhesive joints involves three types of failures, i.e. interfacial failure, transient failure and cohesive failure,[1] as depicted in Figure 4. Transient failure implies a mixed mode of interfacial and cohesive failures. If the surface is not properly treated before adhesion, the interfacial failure occurs. If the adhesion is decent, then cohesive failure occurs. In FE analysis, a representative quarter model, considering the cross-sectional symmetry of the specimen, was used for analysing the shear impact failure of an adhesive joint, as shown in Figure 5. A commercial FE analysis program LS-DYNA 97.1 was used. Solid elements were applied on the adhesive and adherend parts. An elasto-plastic material, which could be deleted when a plastic strain reaches a

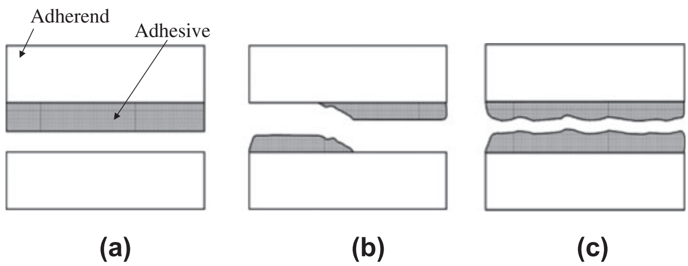


Figure 4. Failure modes of the adhesively bonded joints. (a) Interfacial failure, (b) Transient failure and (c) Cohesive failure.

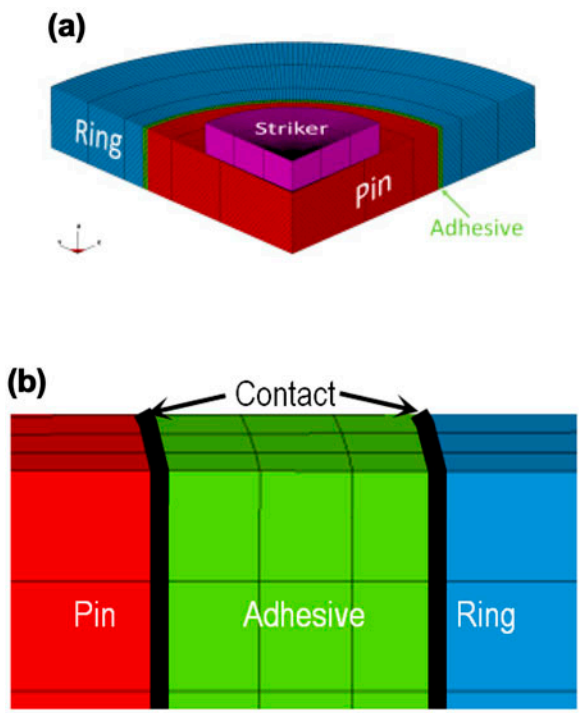


Figure 5. FE model. (a) Oblique view and (b) Magnified view.

failure strain, was assigned to solid elements in the adhesive part. Also, this material can express the shift in yield point depending upon the strain rates, as shown in Equation (1),

$$\sigma_y\left(\varepsilon^p_{\text{eff}}, \dot{\varepsilon}^p_{\text{eff}}\right) = \sigma^s\left(\varepsilon^p_{\text{eff}}\right) + \sigma^i_y\left(\frac{\dot{\varepsilon}^p_{\text{eff}}}{C}\right)^{1/p} \quad (1)$$

where σ_y is the yield stress, $\varepsilon^p_{\text{eff}}$ is the plastic strain, $\dot{\varepsilon}^p_{\text{eff}}$ is the plastic strain rate, σ^s is the static stress, σ^i_y is the initial yield stress and C and p are strain rate parameters.[18,19] About 40 MPa of yield stress, 45 MPa of tensile strength and 7% of failure strain were reported for the C-type epoxy adhesive by UNITECH Co. Ltd.[14] Element deletion in FE analysis would stimulate the cohesive failure of the adhesive part.

Elements for the striker and adherends were defined by a rigid body material. The ring part was stationary; on the other hand, the striker and the pin were only able to translate along the vertical direction. The incident speeds of the striker were chosen as 4 and 5 m/s and the striker mass was set to be 20 kg, in accordance with the impact test.

Tiebreak-type contact option was applied to the gap between adhesive and adherends, i.e. adhesive and pin/ring, as shown in Figure 5(b), to simulate the interfacial failure, i.e. the separation between adhesive and adherends, owing to lack of adhesion. Adhesion consists of normal and shear components, and Equation (2) expresses the failure condition of tiebreak contact.

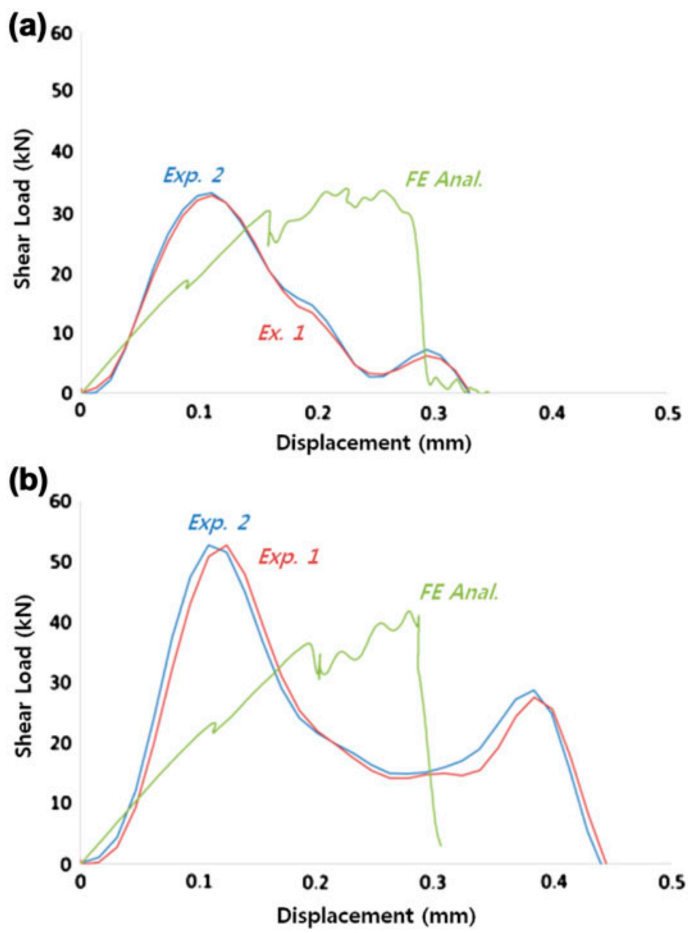


Figure 6. Comparison between experiment and FE analysis. (a) Incident velocity: 4 m/s and (b) 5 m/s.

$$\left(\frac{\sigma_n}{S_n}\right)^2 + \left(\frac{\sigma_s}{S_s}\right)^2 \geq 1 \tag{2}$$

where σ_n is the normal stress, σ^s is the shear stress, S_n is the normal strength of adhesion and S_s is the shear strength of adhesion.[18]

4. Results and discussion

Load-displacement curves from both the impact test and FE analysis are shown in Figure 6. Unnecessary higher frequency components were removed from the FE analysis curves by an SAE J211 filter.[20] From the impact test, maximum loads of 33.3 and 52.8 kN were observed at speeds of 4 and 5 m/s, respectively. Also, it was found from the impact test that the adhesive joint withstood against the impact load during 0.3–0.5 mm displacement region, i.e. less than a tenth of its thickness, and FE analysis supported these trends. As shown in Figure 6, shear load, obtained from FE analysis, fluctuated owing to the interfacial failure and cohesive failure in turns, and it was observed

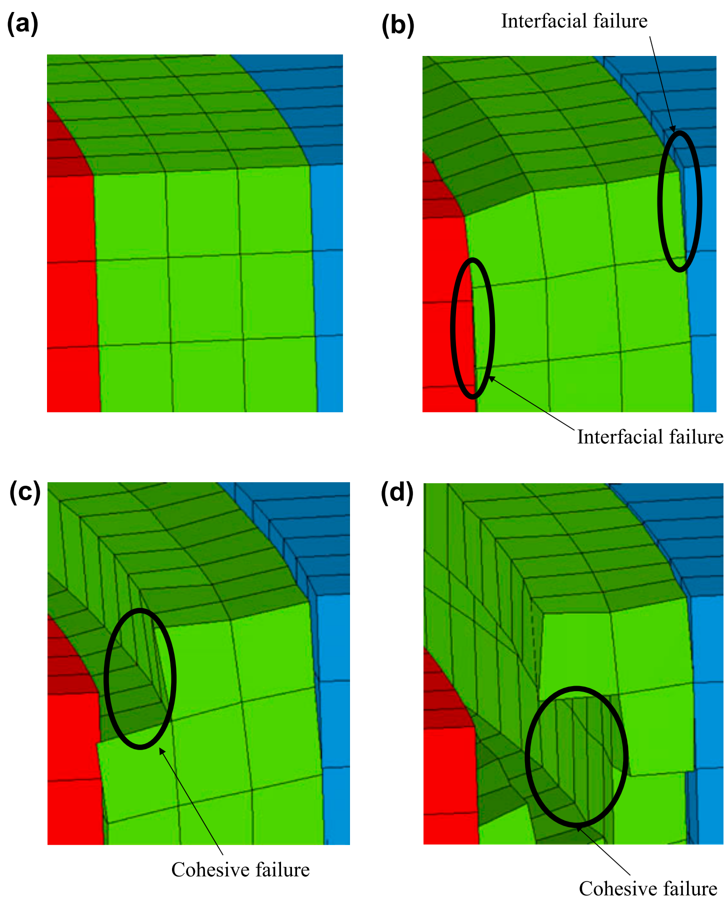


Figure 7. Deformation (5 m/s case). (a) Initial state, $t = 0$ msec. (b) $t = 0.35$ msec. (c) $t = 0.06$ msec. (d) $t = 0.075$ msec.

Figure 8. Adhesives in adherends.

Table 2. Comparison between experiment and analysis.

	Vin (m/s)	Exp. 1	Exp. 2	FE anal.
Max. load (kN)	4	33.4	32.9	33.1
	5	52.8	52.8	43.5
Energy absorbed (J)	4	4.6	4.5	6.6
	5	10.2	9.8	7.5

that shear load was abruptly dropped after completion of adhesive failure while 0.2–0.3 mm through the thickness directional displacement of the adhesive part. FE analysis revealed that partial interfacial failure occurred first in the adhesive joint followed by cohesive failure, as illustrated in Figure 7. If adhesion strength had increased further and become higher than the failure strength of the adhesive, cohesive failure would have occurred first instead of interfacial failure.

Figure 8 shows the appearance of adherend after the experiment. It was also found that transition failure was generated where interfacial failure and cohesive fracture occurred in turns from the surfaces of the adhered pin and ring. Impact adhesive strength variation is expected to be investigated with respect to surface roughness in the near future. The comparison between test results and FE analysis results were listed in Table 2. It was observed that the current FE model showed comparatively good agreement with impact tests both for maximum loads quantitatively and qualitative transition failure qualitatively.

5. Conclusions

In this study, the shear impact characteristics of an adhesive for a mechanical structure at different striker velocities (4 and 5 m/s) were performed through finite element analysis and impact test. Maximum loads of 33.3 and 52.8 kN were found under striker velocities of 4 and 5 m/s, respectively. The area on which load was imposed was within 0.3–0.5 mm, which was less than a tenth of the width of 5 mm in the adhesive joints of ring and pin. FE analysis revealed that the partial interfacial failure occurred first in the adhesive joint, followed by cohesive failure. If adhesion strength had increased further and become higher than the failure strength of the adhesive, cohesive failure would have occurred first instead of interfacial failure. It was also found that transition failure was generated where interfacial failure and cohesive fracture occurred in turns from the surfaces of the adhered pin and ring. Impact adhesive strength variation is expected to be investigated with respect to surface roughness in the near future. It was observed that the current FE model showed comparatively good agreement with impact tests for both maximum loads quantitatively and qualitative transition failure qualitatively.

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