Practical Failure Criterion of Spot Weld for Crash Simulation

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1 Abstract

This paper proposed a practical failure criterion of spot welds for combined loading condition for crash simulation. The tests were designed to obtain the failure load of a spot weld under combined loading condition. The seven types of experimental test were conducted to obtain the component of spot weld failure criterion. The failure criterion consists of moment component including normal and shear force. Components of each failure test are obtained from finite element analysis results which are called as hybrid method. The proposed criterion was considered to use Wung [1, 2] model except torsion term. It was found that the criterion of mild steel could be expressed as a function well known in previous researches, however the failure criterion of high strength steel and advanced high strength steel could not be described with it. Here we propose new approach. The newly proposed failure criterion is well applied to hat-specimen simulation result.

2 Research Background

Automotive design ground rule has been changed for improvement of crash safety and the better fuel efficiency. Limiting performance of an auto-body has been the crash safety as considering key design issues such as crash regulations and environmental regulations. One of the challenging issues in the automotive industry is the improvement of crashworthiness together with the light weight design. Actual crash test cost for evaluation of the crashworthiness of an auto-body increase consistently due to strict regulations for enhancement of the car crash safety. As an alternative method to evaluate the crashworthiness of auto-body structures, computer simulations are widely used in the automotive industry [3]. The proper failure prediction of spot welds is indispensable for the accurate simulation of the crash test of auto-body structures prior to actual tests because a typical modern vehicle body contains 2000 to 5000 spot welds. Spot weld failure significantly affects the crashworthiness and the deformation behavior of auto-body structures in a car crash simulation. Because the impact load transferred from one part to another part through the spot weld is abruptly changed with the failure of spot welds, deformation behaviors of the auto-body structures usually result in large discrepancies between the experiment and the finite element analysis after joined components are separated. Therefore, it is extremely important to understand the strength and failure behavior of spot welds under impact loading conditions [4, 5].

3 Research Objective

Spot weld fracture is a critical issue in crash simulation. Main object of this paper is to develop the practical spot weld failure model in crash simulation.

4 Conventional Spot Weld Failure Model

Generally, estimation of the failure characteristics of spot welds has been performed with lap-shear tests, coach-peel tests, and cross-tension tests. Zuniga and Sheppard [6] carried out failure tests for spot welds of high strength steels and investigated the failure mechanism of the lap-shear test and the coach-peel test. Their research revealed that the failure mechanism of the lap-shear test could be described by localized necking of the base metal near the interface between the heat-affected zone (HAZ) and the base metal. Chao [7] proposed a failure criterion based on the failure loads of cross-tension and lap-shear specimens. It is, however, insufficient to provide an accurate failure criterion that describes the behavior of spot welds under combined loading conditions, because spot welds in the auto-body structures are subjected to a complicated loading condition with deformation by car crash. Lee et al. [8], Barkey and Kang [9], Madasamy et al. [10], Langrand and Combescure [11], and Langrand and Markiewicz [12] proposed testing fixtures to provide various loading conditions including

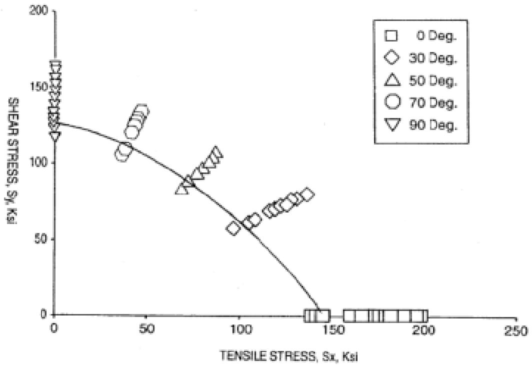


Fig.1: Spot weld failure model proposed by Lee et al. [8]

pure normal, mixed normal/shear, or pure-shear loads on a spot-welded specimen by changing the position of the fixture.

The coefficients that constitute a force-based failure criterion were determined by a regression analysis from the failure strength data of the spot weld. Lee et al. [8] proposed a test methodology under the combined loading conditions and the spot weld failure model based on experimental results. The failure criterion is expressed as

$$\left(\frac{f_s}{F_S}\right)^n + \left(\frac{f_n}{F_N}\right)^n = 1 \qquad (1)$$

Here, F_N and F_S are the normal failure load and the shear failure load of a spot weld, respectively. The variable n is a shape parameter. The coefficients that constitute their failure model are obtained using the least square method to minimize the discrepancy between the experimental data and interpolated data. Fig. 1 shows the proposed spot weld failure model.

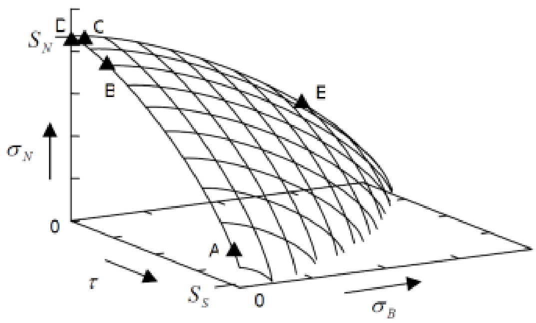


Fig.2: Spot weld failure model proposed by Wung et al. [1, 2]

In the result of Lee et al. [8], spot weld failure criterions are composed of the normal failure load and the shear failure load. Wung [1] and Wung et al. [2], however, suggested the failure mechanism based on the normal load, shear load, bending and torsion. Wung [1] defined the failure modes of a spot weld by three kinds of mechanism, and proposed the failure criterion based on a failure force. The failure criterion is expressed as

$$\left(\frac{f_s}{F_S}\right)^\alpha + \left(\frac{m_b}{M_b}\right)^\gamma + \left(\frac{f_n}{F_N}\right)^\mu + \left(\frac{m_t}{M_t}\right)^\beta = 1 \qquad (2)$$

Here, F_N, F_S, M_b and M_t are the normal failure load, the shear failure load, the failure moment and the failure torsion of a spot weld, respectively. The variables of α, β, γ and μ are shape parameters. The coefficients that constitute their failure model are obtained using the least square method to minimize the discrepancy between the experimental data and interpolated data. Fig. 2 shows the proposed spot weld failure model.

5 Newly Proposed Spot Weld Failure Model

5.1 Experimental procedure

Prior to spot welding of a specimen, the specimen was wiped with dilute acetone solution using a cloth in order to remove grease and dirt from its surface. Spot welding was then performed using a static spot/projection welding machine. The welding conditions were determined after several U-tension tests with the industry standards to guarantee a button-type failure.

In this paper, it is assumed that influential factors on spot weld failure are normal load, shear load and bending, because torsion can be negligible in the automotive structure. Based on this assumption, the spot weld failure model is expressed as

$$\left(\frac{f_n}{F_N}\right)^{\alpha}+\left(\frac{f_s}{F_S}\right)^{\beta}+\left(\frac{m_b}{M_b}\right)^{\gamma}=1 \qquad (3)$$

Here, F_N, F_S and M_b are the normal failure load, the shear failure load and the failure moment of a spot weld, respectively. The variables of α, β and γ are shape parameters. In order to obtain the normal, shear and bending failure loads, failure tests of the spot welds were conducted at different initial loading angles of 0°, 30°, 45°, 60° and lap-shear test was done using the testing fixture and specimens. Pure-shear test at a loading angle of 90° was carried out using the fixture and specimen proposed by Ha and Huh [13]. The loading angle indicates the imposed angle of a spot-welded specimen with respect to the loading direction. In addition, lap-shear tests were conducted in order to obtain the failure loads of spot welds. Testing procedures are as shown in Fig. 3. Failure tests were conducted using an INSTRON 5583 device with a cross-head speed of 3.0 mm/min until the specimen was separated into two components. The load and the displacement were measured simultaneously at each test. The load was measured with the load cell equipped in the testing machine and the displacement was calculated from the relative movement of the two pull bars.

5.2 Hybrid method to determine the coefficients of newly proposed failure model

It is impossible to determine the coefficients of proposed failure model directly from the experiments because combined loads acts on spot welds during failure tests. Acting loads on spot weld are shown in Fig. 3 with respect to the testing conditions. In order to determine the failure loads and shape parameters of failure model, decomposing failure loads have to be conducted by the hybrid experimental-numerical procedure which is called as the hybrid method [14].

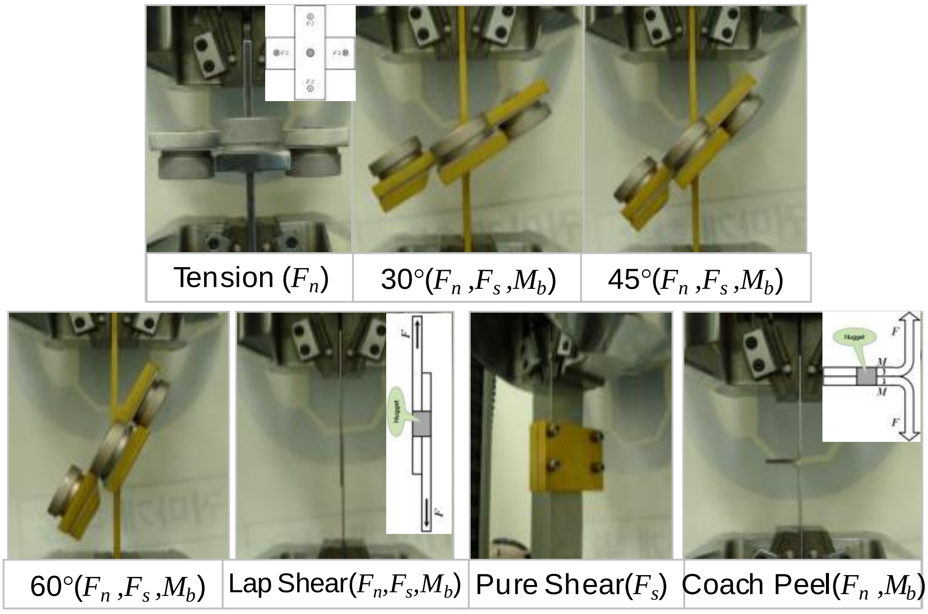


Fig.3: Failure test procedure for newly proposed failure model

Hybrid method is utilized to determine the onset of fracture of specimen. The displacement fields on the specimen surface are measured using either two- or three-dimensional digital image correlation (DIC). Based on the DIC measurements, the instant of onset of fracture (not the location) is defined by the first detectable discontinuity in the measured displacement field at the specimen surface. Subsequently, a finite element simulation is performed for each experiment. Post-processing of those simulations gives then access to the evolution of the stress triaxiality and the equivalent plastic strain.

To obtain the failure load components with respect to failure test conditions, hybrid method based on the failure loads is utilized. Based on the failure loads obtained in failure test, the instant of onset of spot weld failure is determined. Subsequently, a finite element simulation is performed for each experiment. Post-processing of those simulations gives failure load components acting on spot welds such as normal, shear and bending loads. These failure load components are plotted on the plane consisting of normal load, shear load and bending axes. Fig. 4 shows the hybrid method to obtain the failure load components from the failure tests.

5.3 Construction of newly proposed failure model

Based on the hybrid method, newly proposed failure model is constructed by Eq. (3) as shown in Fig. 5. The coefficients that constitute newly proposed failure model are obtained using the least square method to minimize the discrepancy between the experimental data and interpolated data.

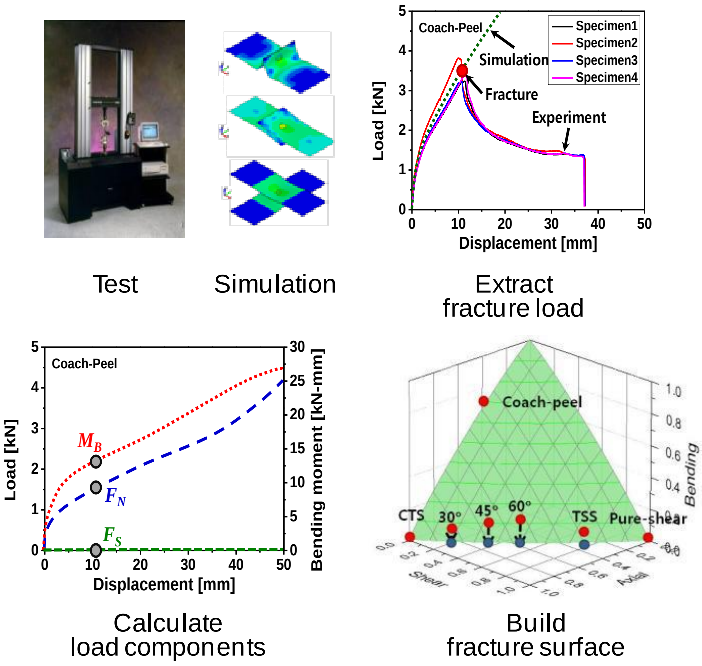


Fig.4: Hybrid method to obtain the failure load with respect to test conditions

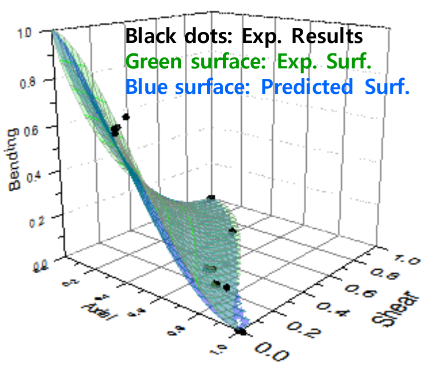


Fig.5: Spot weld failure surface constructed by newly proposed failure model

Generally, the surface of the conventional spot weld failure models is convex shape. However, the shape of failure surface is changed to material strength. As the material is stronger, the moment effect to spot weld failure is significant. In this paper, materials with various levels of strength were tested to develop the practical spot weld failure model as shown in Fig. 6. The shape of failure surfaces change from convex to concave as the material strength increases. Fig. 7 shows failure surfaces of the proposed model and that of the conventional model. Conventional models tend to evaluate the spot weld fracture to be excessively safe. Therefore, newly proposed failure model have to be utilized in the crash simulation to predict the spot weld failure.

The proposed failure model for spot weld in this paper can predict the spot weld failure accurately. However, a number of failure tests and analysis have to be conducted to construct the failure model. In order to construct the failure model simply, prediction equations were developed for the 6 coefficients of the proposed spot weld failure model. These equations are expressed as

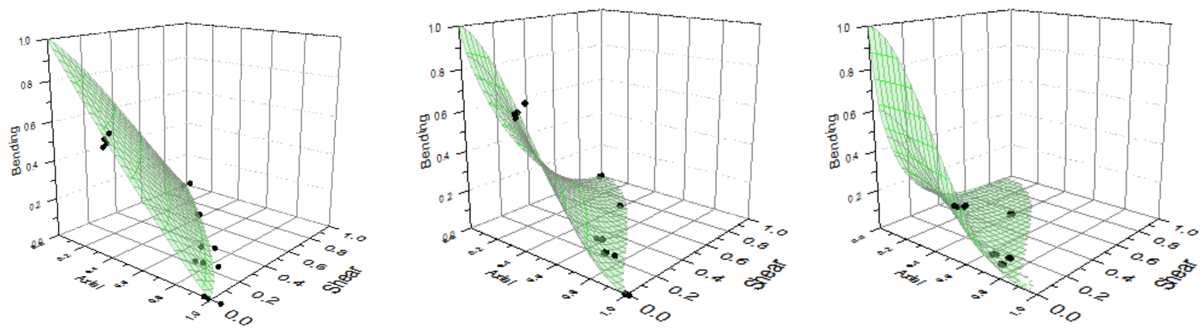
$$F_n, F_s, M_b = f(t, \sigma_{TS}, \phi) \tag{4}$$

$$\alpha, \beta, \gamma = f(t, \sigma_{TS}, \phi) \tag{5}$$

Here, t, σ_{TS} and ϕ are thickness, tensile strength and nugget ratio, respectively. 6 coefficients are determined by the function of thickness, tensile strength and nugget ratio. Blue failure surface shown in Fig. 5 is constructed by the prediction equations. Predicted failure surface describes the failure surface constructed by failure tests and hybrid method.

5.4 Verification of the proposed failure model

Crash simulation of a rectangular hat specimen was carried out to verify the newly proposed failure model. LS-DYNA was utilized to perform the crash simulation. Spot weld failure assessment system (SWFAS) was developed, which is based on the newly proposed failure model and LS-DYNA result file such as SWFORC to confirm the failure spot welds from the crash simulation results. SWFAS program informs the failure location of spot welds and the degree of failure risk to SWFAS program users, as shown in Fig. 8.



(a) (b) (c)

Fig.6: Failure surface of spot welds with respect to the material grades: (a) DQ; (b) 440R; (c) 780DP

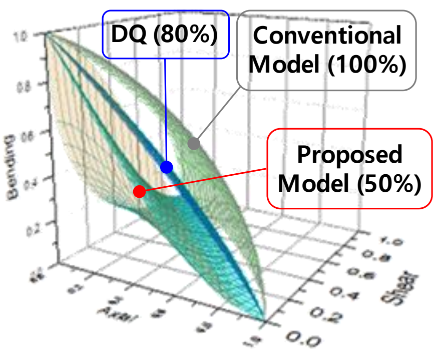
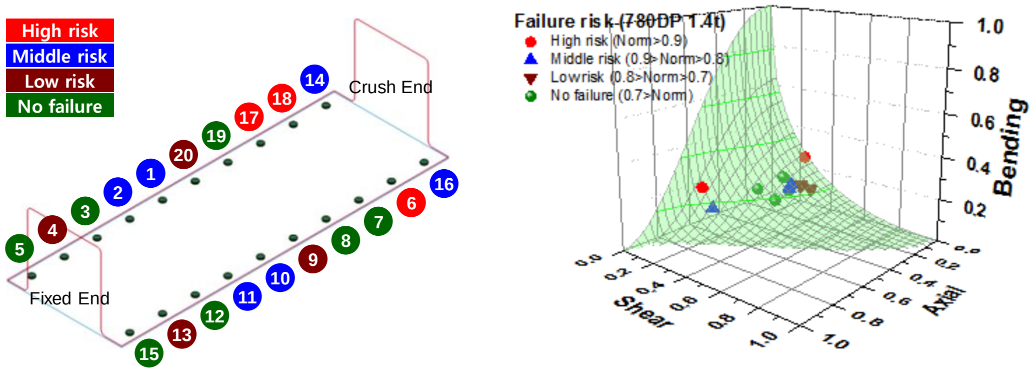


Fig.7: Failure surfaces of the proposed model and the conventional model



(a) (b)

Fig.8: Results of SWFAS program after crash simulation: (a) failure location; (b) degree of failure risk

(a) (b)

Fig.9: Deformed shape of the rectangular hat specimen: (a) simulation; (b) experiment

SWFAS program assesses spot weld failure by LS-DYNA result file, SWFORC, without additional simulation. Proposed failure model also predict the failure location and the degree of failure risk as shown in Fig. 9. Therefore, proposed failure model and SWFAS program have to be used in order to predict the failure of spot weld in crash simulations.

6 Summary

A number of automotive steel sheets are evaluated and analyzed by various spot-weld tests. The shape of failure criterion to material strength is changed. As the material is stronger, the moment effect to spot weld failure is significant. The failure surface becomes concave and sharp as the material strength increases. The rectangular hat specimen experimental test results for spot weld failure are well consistent with the simulation results by considering criterion proposed in this paper.

7 Literature

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