Prediction of Spot Weld Failure for Automotive Steels

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Abstract: Spot weld failure has a great influence on the crashworthiness of a vehicle since an automotive body is mostly assembled by spot welding. Spot weld failure was not a serious problem when using low strength steel, but as the strength of steels increases, spot weld failure became a hot issue for crash performance due to the low spot weld strength compared to material strength. Nowadays, the car design is based on CAE, and the crashworthiness is evaluated from crash simulation. Spot weld failure is a critical factor causing the discrepancy between the actual crash performance and simulation result. Of course, car designers want to get accurate simulation results and design to avoid spot weld failure based on simulation. There are a lot of studies on spot welding failure, but It is necessary to further enhance the accuracy.

In this paper, we study how to predict accurate spot weld failure by macroscopic analysis of spot weld failure. Normal, shear, bending, and torsional load components act on spot welds, and many spot weld failure model consider that they act independently, destroying the spot weld. In this paper, normal and bending load components are considered together because loading direction and plane of normal and bending components are same. Spot weld failure model that normal and shear load components act independently and there is the interaction of normal and bending components, is newly proposed. Here, torsional component is ignored because of low influence on an automotive body.

Spot weld failure tests are performed for various automotive steels, and coefficients of spot weld failure models are derived. Since an automotive body has mostly heterogeneous stack-ups of the strength and the thickness, the spot welding failure tests for heterogeneous stack-ups are also performed and it is verified that the new model describes dissimilar stack-ups well. Compared to conventional models, the new model has an advantage in the simplicity and the accuracy. Finally, the predicting method of coefficients of spot weld failure models is developed to consider spot weld failure in the crash simulation without experiments.

Keywords: Spot weld failure, Hybrid method, Cross tension, Coach peel, Heterogeneous stack-up, Plug fracture

1 Introduction

Improvement of crashworthiness becomes one of the challenging issues in auto industries together with the light weight design. Actual crash test cost to evaluate the crashworthiness of the auto-body structure become larger due to tighten regulation for a car crash. Thus, computer simulation as an alternative method to evaluate the crashworthiness of the auto-body structure is widely used in the automotive industry [3]. In order to estimate the crashworthiness properly, the correct failure prediction of a spot weld is indispensable for the crash simulation [4], [5]. Rupture of a spot weld is likely to occur prior to failure of the base metal when a large load is applied to the auto-body structure since extremely high stress is concentrated at the interface between the nugget and the base metal [6]. Because the impact load transferred from one part to another part through a spot weld is abruptly changed after the spot weld fails, deformation behaviors of the auto-body structure usually reveal large discrepancies between experiment and simulation after joined components are separated.

Research on the failure characteristics of a spot weld has been investigated over the past few decades. Especially, it is necessary to estimate the strength of spot welds under various loading modes in order to provide a failure criterion of a spot weld for the structural analysis or crashworthiness assessment of the auto-body structures using the finite element analysis. Lee et al.[7], Barkey and Kang [8], Madasamy et al. [9] and Langrand and Combescure [10] proposed testing fixtures to provide various loading conditions including pure axial, mixed axial/shear, or pure shear loads on a spot-welded specimen through changing the position of the fixture. The failure strengths of the spot weld under combined loading conditions were utilized to provide the failure criterion. The coefficients that constitute a force-based failure criterion were determined by a regression analysis from the failure strength data of the spot weld. Similarly, Lin et al. [11], [12] proposed a test methodology with a different type of test fixture. They analyzed and clarified the failure mechanism of spot welds in square-cup specimens made from the mild steel and the HSLA steel under combined loading conditions. After failure tests of the spot-welded specimens using four fixture sets designed by them, an engineering failure criterion was proposed to be in quadratic form in terms of the normalized axial and shear loads with consideration of the sheet thickness and the nugget radius under combined loading conditions. Although the testing fixtures proposed by previous researchers could impose various combinations of axial and shear loads on the spot weld efficiently by changing the loading position of the fixtures, it is impossible to consider

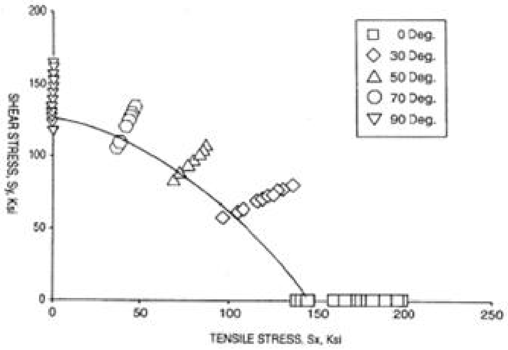


Fig.1: Spot weld failure model proposed by Lee et al. [9]

the change of load histories acting on the spot weld due to the rotation of the nugget during the failure tests. Since the rotation of the nugget during the failure tests alters the ratio of the axial load and the shear load acting on the spot weld, the change of the load histories by the rotation of the nugget have to be considered when the ration of the axial load and the shear load is calculated using the failure load.

Recently, spot weld failure models are proposed based on the stress acting on the spot welded parts and microscopic approaches. Seeger et al. [13] and Seeger et al. [14] proposed a stress-based failure criterion which was determined by a regression analysis from the failure test results. In order to construct the failure surface, KSII tests from 0° to 90° and peel test were conducted. Yang et al. [15] proposed a testing protocol for the purpose of creating spot weld failure parameters of a stress-based failure criterion which is implemented in LS-DYNA software. Sandahl et al. [16] proposed the semi-physical modeling method which can predict the spot weld failure and macro cracks.

This paper proposes new spot weld failure model that considers the interaction of normal and bending components, and calculates the stress by dividing the load by the area of plug fracture. In order to obtain coefficients of failure models, a lot of spot weld fracture tests for homogeneous and heterogeneous stack-ups were carried out. Heterogeneous stack-ups are considered as the combination of two different materials because plug fracture occurs at each base metal. Finally, the predicting method of coefficients of spot weld failure models is developed for accurate simulation considering spot weld failure without experiments/

2 Experimental Procedure for Spot Weld Failure Model

2.1 Experimental Procedure for Spot Wed Failure Load

Chao [17] 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. Therefore, a large researcher proposed testing fixtures to provide various loading conditions including pure normal, mixed normal/shear, or pure-shear loads on a spot-welded specimen by changing the position of the fixture.

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 [18]. 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. 2. 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. These tests involve one or two load components. Of course, inclined tension tests and lap shear test have 3 load components but bending is relatively small. So, there is not a case under complex loading condition where each three load component acts meaningfully. 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.

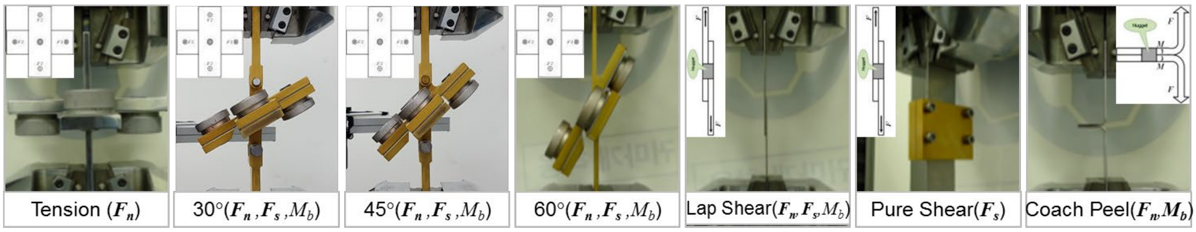


Fig.2: Failure test procedure for newly proposed failure model

2.2 Hybrid Method to Determine Coefficients of Failure Models

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. 2 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 [19].
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.
Hybrid method based on the failure loads is utilized in order to obtain the failure load components with respect to failure test conditions. Based on the failure loads obtained in failure tests, 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. The hybrid method procedure is as follows:

a. Failure tests are performed with respect to loading conditions.
b. Finite element simulations are performed for each experiment.
c. Based on the failure loads obtained in failure test, the instant of onset of spot weld failure is determined. Failure loads are extracted comparing experiments with simulations.
d. Post-processing of those simulations gives failure load components acting on spot welds such as normal, shear and bending loads.
e. These failure load components are plotted on the plane consisting of normal, shear and bending axes.

Fig. 3 shows the hybrid method to obtain the failure load components from the failure tests.

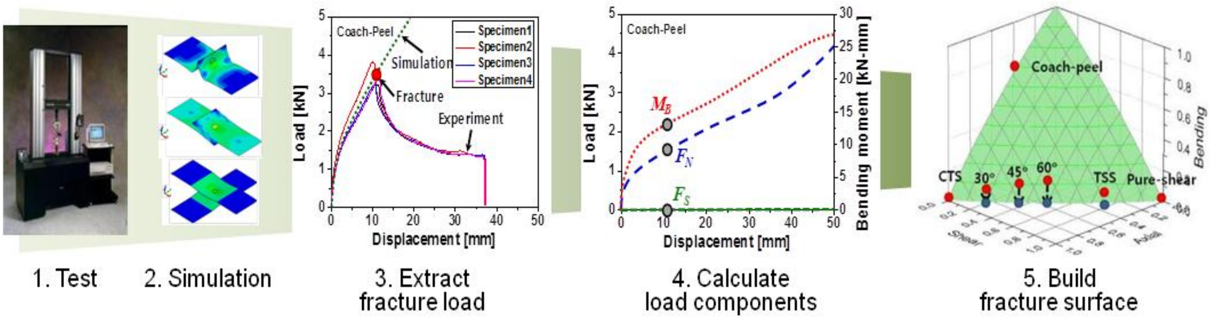


Fig.3: Hybrid method to obtain the failure load with respect to test conditions

3 Proposal of New Spot Weld Failure Model

3.1 Conventional Spot Weld Failure Models

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. [7] proposed a test methodology under the combined loading conditions and the spot weld failure model based on experimental results such as equation (1).

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

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.

In the result of Lee et al. [7], 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 as equation (2).

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

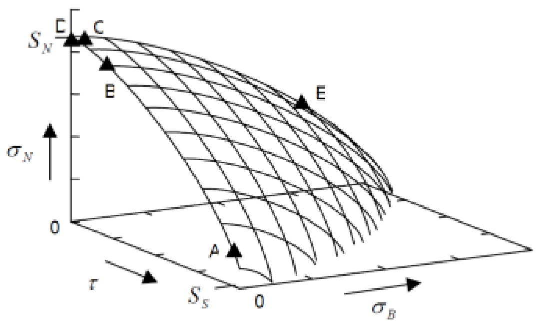


Fig.4: Spot weld failure model proposed by Seeger et al. [13], [14]

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.

The coefficients that constitute a stress-based failure criterion were determined by a regression analysis from the failure strength data of the spot weld. This 3-D failure criterion describes a polynomial failure surface which is proposed by Seeger et al. [13] as shown in Fig. 4. The spot weld fails if the sum of components of the internal normal, bending and shear stresses is above the surface. The failure criterion is expressed as equation (3).

$$\left(\frac{\sigma_N}{S_N}\right)^{n_N} + \left(\frac{\sigma_B}{S_B}\right)^{n_B} + \left(\frac{\tau}{S_S}\right)^{n_S} = 1 \qquad (3)$$

Here, σ_N, σ_B, τ are the normal failure stress, the bending failure stress, the shear failure stress of a spot weld, respectively. The variables of n_N, n_B and n_S 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.

Most spot weld failure models are considered that each load component operates independently and the principle of superposition is established. Toyota Motor[20] developed a stress based failure model as equation (4) that is based on the peak axial and shear stresses, and axial and bending components are linearly combined. Here, area for calculating stress is $\pi d^2/4$, and d is the diameter of a spot weld.

$$\left(\frac{\sigma_{rr}}{\sigma_{rr}^{FF}}\right)^2 + \left(\frac{\tau}{\tau^F}\right)^2 = 1 \tag{4}$$

3.2 New Spot Weld Failure Model

In order to enhance the accuracy of spot weld failure model, 3 issues are considered in this paper. The first is which fracture mode is acceptable for normal spot weld fracture. A spot weld is fractured in plug fracture, interfacial fracture or partial interfacial fracture. If the welding size is large enough and the nugget is sound, plug fracture occurs instead of interfacial fracture. Automotive industry judges the interfacial fracture to be defective. Therefore, only plug fracture is considered as normal spot weld failure in this paper.

The second issue is whether load components such as normal, shear and bending work independently of each other. Basically, if the direction and the plane are same, it is considered that there is an interaction between two loads. Fig. 5 is the schematic diagram for load components of a spot weld. The direction of shear load component is horizontal, but both directions of normal and bending are vertical because only plug fracture is considered as normal spot weld fracture. It means that normal and bending components are no longer independent of each other. In a viewpoint of fracture plane, stresses by normal and bending components is shear, and stress by shear component is normal.

The last issue is what is the right area for calculating stress. Most stress based failure models use $\pi d^2/4$ as the area of stress. But, as shown in fig. 6, the value, $\pi d^2/4$ indicates the area of interfacial fracture which is unintended fracture mode. The real fracture area for plug fracture is the side plane of a button, and the value is πdt.

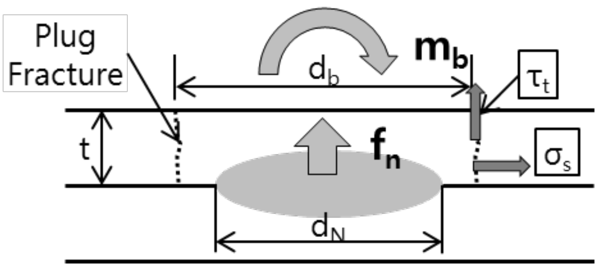


Fig.5: Schematic diagram for load components of a spot weld.

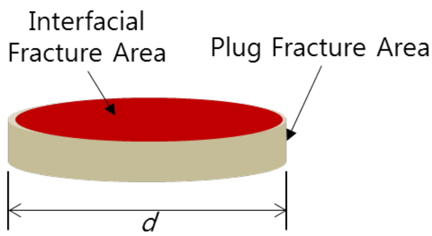


Fig.6: Schematic diagram for fracture area of a spot weld

$$\left(\frac{\tau_t}{\tau_t^F}\right)^\alpha + \left(\frac{\sigma_s}{\sigma_s^F}\right)^\beta = 1 \tag{5}$$

$$\tau_t = \tau_n + c\tau_b \tag{6}$$

$$\tau_n = \frac{f_n}{\pi d_b t} \tag{7}$$

$$\sigma_s = \frac{f_s}{\pi d_b t} \tag{8}$$

$$\tau_b = \frac{4m_b}{\pi d_b^2 t} \tag{9}$$

Considering the three issues mentioned above, equation (5) modified from equation (3) is applied for new spot weld failure model. Here, τ_t is the shear stress by normal and bending load components, and σ_s is the normal stress by shear load component. α and β are shape parameters of fracture surface. It is assumed that normal and bending load components have a linear proportional relation by coefficient, *c* as equation (6). The stress distribution by normal load component is uniform, but that by bending load component is concentrated. Therefore, the effects of normal and bending components on stress are different. The effect of normal component is larger than that of bending component. Stresses of normal, shear and bending components are respectively calculated by equation (7), (8) and (9) considering plug fracture area, πdt. d_b is the diameter of a button. Finally, the equation (10) is derived as the new spot weld failure model. The new model has 5 coefficients which are τ_t^F, σ_s^F, c, α and β.

$$\left(\frac{\tau_n + c\tau_b}{\tau_t^F}\right)^{\alpha} + \left(\frac{\sigma_s}{\sigma_s^F}\right)^{\beta} = 1 \tag{10}$$

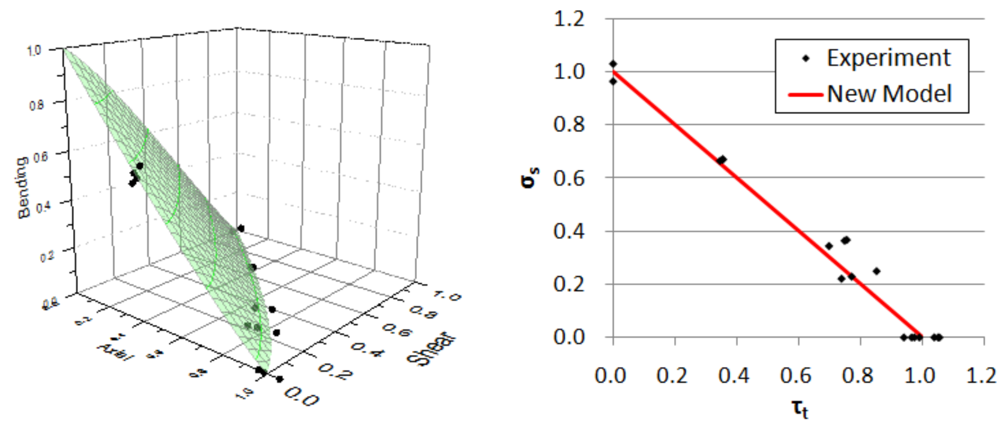
τ_t^F and σ_s^F can be directly calculated by dividing fracture loads of cross tension and pure shear tests by fracture area, πdt. After that, the coefficient, c can be easily obtained by substituting normal and bending load components of coach peel test into equation (6). Other tests except cross tension, pure shear and coach peel is needed to determine shape parameters, α and β.

4 Experimental Results

An automotive body is composed of various materials and the thickness. In this paper, spot weld fracture tests about 42 kinds of automotive steels were performed. The tensile strength of testing materials is from 270MPa to 1500MPa, and the range of the thickness is from 0.55mm to 2.3mm as table 1. The test was repeated more than 3 times for each specimen type, and Wung model and newly proposed model based on the hybrid method are constructed using at least 20 tests per each material. Fig. 7 shows fracture surface of Wung model and newly proposed model about DQ steel. The fracture surface of Wung model is 3 dimensional, but the fracture surface of the new model is 2 dimensional and intuitive. Even if the failure model is accurate, there is an error with the test. Errors of Wung and new models are compared in table 1. Here, the average means the accuracy, and the sum of square and the standard deviation mean concentricity. The new model is a little bit better that Wung model, but the difference is not significant.

Table 1: Comparison of Wung and New models about 42 homogeneous stack-ups.

No.	Material	Thickness (mm)	Error, e - Wung Model			Error, e - New Model		
			Average	Σe^2	St. Dev.	Average	Σe^2	St. Dev.
1	DQ	0.55	0.1%	0.04	4.8%	1.5%	0.05	5.3%
2	440R	1.2	-1.1%	0.10	7.4%	-2.0%	0.10	7.2%
3	440R	1.4	-0.4%	0.05	5.1%	-1.6%	0.07	5.9%
⋮								
126	980DP	1.2	-1.5%	0.17	9.0%	5.6%	0.48	14.3%
128	590DP	1	-0.1%	0.02	3.4%	-4.9%	0.12	5.7%
129	780DP	1	-0.4%	0.17	9.1%	-0.5%	0.18	9.1%
130	590TRIP	1.2	0.5%	0.13	7.8%	-1.4%	0.06	5.0%
131	DQ	0.7	-1.7%	0.11	7.4%	0.8%	0.14	8.4%
Average			**-2.3%**	**0.43**	**11.4%**	**-3.4%**	**0.32**	**10.6%**



(a) (b)

Fig.7: Failure surface of DQ steel: (a) Wung model; (b) New model.

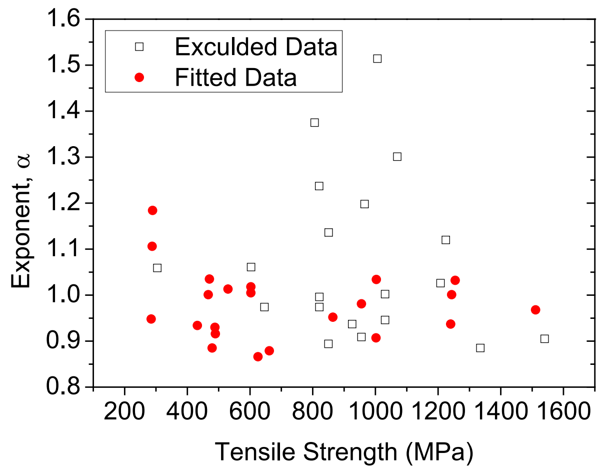


Fig.8: Variation of shape parameter, α with respect to the tensile strength.

Wung model not considering the torsional term has 6 coefficients, and these coefficients vary according to the welding parameter such as the thickness, the weld size and the tensile strength. Coefficients of the new model related to spot weld strength, τ_t^F, σ_s^F and c also vary, but shape parameters, α and β has little variation of the value. As shown in Fig. 8, the range of α is usually 0.85~1.1 and it may be assumed that α is same to β. Furthermore, assuming both α and β are unity, the error is not large. If shape parameters are 1 as Fig. 7(b), the fracture surface becomes linear line. This is very important because the spot weld failure model becomes very simple as equation (11). There are only 3 coefficients, so only 3 kinds of spot weld fracture tests such cross tension, pure shear and coach peel are necessary to determine coefficients of the new model.

$$\left(\frac{\tau_n + c\tau_b}{\tau_t^F}\right) + \left(\frac{\sigma_s}{\sigma_s^F}\right) = 1 \qquad (11)$$

As shown in Fig. 7(a), the number of load components for homogeneous stack-up are usually one or two. Even if there are normal, shear and bending components in lap shear and inclined tension tests, bending component is small. Originally, inclined tension is designed for complex loading condition, but the bending component is not effective for homogeneous stack-ups due to symmetric boundary condition. It means that the effect of bending is mainly determined by coach peel test. Because there is no shear component in coach peel test, the complex loading condition is not considered in obtaining the fracture surface of spot weld failure model. Spot weld failure models are verified by spot weld fracture tests for heterogeneous stack-ups which has considerable bending component in inclined tension tests due to asymmetric material and the thickness. Totally, spot weld fracture tests were carried out for 23 heterogeneous stack-ups such as table 2.

Table 2: Comparison of Wung and New models about 23 heterogeneous stack-ups.

No.	Material 1	Material 2	Error, e - Wung Model			Error, e - New Model		
			Average	Σe^2	St. Dev.	Average	Σe^2	St. Dev.
54	590DP 1.2t	590DP 1.0t	6.4%	0.92	19.4%	-8.5%	0.63	14.6%
55	780DP 1.2t	340Y 1.5t	105.7%	27.54	66.1%	7.7%	0.46	14.4%
56	780DP 1.2t	590DP 1.0t	7.6%	1.63	26.1%	2.1%	0.78	18.7%
⋮								
112	590DP 1.2t	1180TRIP 1.4t	8.5%	0.77	17.0%	9.2%	0.64	14.7%
113	780DP 1.0t	980DP 1.0t	-8.4%	0.31	9.1%	-7.7%	0.31	9.6%
114	980DP 1.2t	590TRIP 1.2t	22.4	2.75	28.0%	23.5%	2.46	24.4%
115	980DP 1.2t	1180TRIP 1.4t	38.4%	3.81	19.0%	35.2%	3.30	18.6%
116	590TRIP 1.2t	1180TRIP 1.4t	9.7%	16.74	86.7%	-7.7%	7.93	59.5%
Average			**13.0%**	**3.36**	**25.1%**	**8.8%**	**1.44**	**18.2%**

It is important how to determine spot weld failure for heterogeneous stack-ups. In chapter 3, since it is determined that only plug fracture is normal mode, the fracture of a spot weld always occurs at each sheet independently, not the nugget. Therefore, it can be assumed that the fracture surface of heterogeneous stack-up is determined by smaller value of the combination of each two surface. It is found that strong materials don't always have larger fracture surface from spot weld fracture tests. For example, Gigasteels generally have higher shear strength of a spot weld, but lower cross tensile strength than conventional steels. In such case, the fracture surface can be expressed as shown in Fig. 9. That is, the fracture surface of the heterogeneous stack-up is determined not by the test of the heterogeneous stack-up but by the fracture surface of each material. The errors of Wung model and the new model about 23 heterogeneous stack-ups are compared in table 2. Unlike the homogeneous stack-ups, the new model shows a much better error that Wung model. Even if the new model has less coefficients that Wung model, the new model has better accuracy for complex loading in which bending component is considerable.

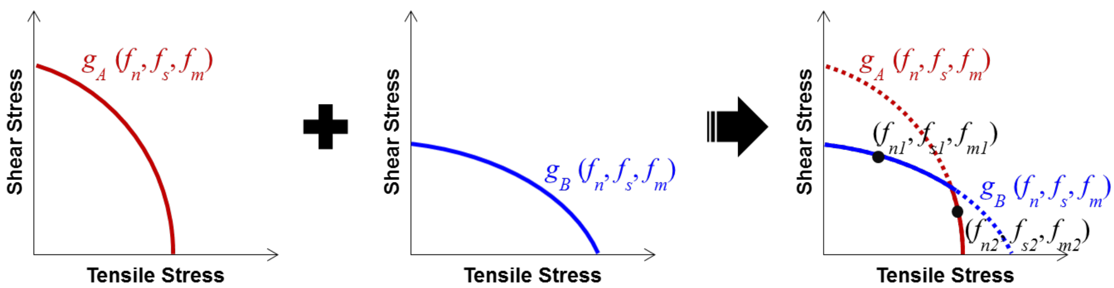


Fig.9: Consideration of fracture surface for dissimilar stack-up.

5 Predicting Coefficients of Spot Weld Failure Model

Based on the database of spot weld failure models for 42 homogeneous stack-ups, it is found that the coefficients of spot weld failure model vary with the weld size, the thickness of material and material strength. Considering that an automotive body is assembled with thousands of spot weld, a lot of spot weld fracture tests about a great combination of spot weld parameters are necessary for obtaining coefficients which is applied to crash simulation. It is practically impossible. Therefore, in this paper, the predicting method for coefficients of spot weld failure models is developed by the analysis of correlation between coefficients of spot weld failure models and spot weld parameters such as the thickness, the weld size and tensile strength. From the analysis, it is confirmed that coefficients of Wung model are function of the thickness, the weld size and the tensile strength, but the new model are affected by only the tensile strength. That is, coefficients of Wung model and the new model can be respectively calculated by regression functions such as equation (12) and (13). The regression function of the new model has only 1 variable, the tensile strength because the thickness and the weld size are already considered in stress calculation. Coefficients of conventional stress based models are still related to the thickness and the weld size. This reason is that the stress is calculated by wrong way, exactly speaking, fracture area.

$$F_s = f_1(t, \phi, \sigma_{TS}) \quad (12)$$

$$\tau_t^F = g_1(\sigma_{TS}) \quad (13)$$

The prediction models are compared with experiments of a coupon specimen for homogeneous stack-ups as table 3. The accuracy of both prediction of Wung model and the new model are similar to that of the experiment, and the prediction of the new model is better than that of Wung model. For homogeneous stack-ups, conventional model does not have significant error because the bending component does not exist with the shear component on a coupon test simultaneously. But, if bending component is applied incorrectly to the spot weld failure model, considerable error may occur in coupon tests for heterogeneous stack-ups or a real structural part. So, Wung model still has much error for heterogeneous stack-ups in table 4 even if the new model has great improvement in error compared to the experiment of table 2. It is confirmed that the prediction of coefficients of spot weld failure models is very useful and still accurate, and the new model is defined well to predict the spot weld failure.

Table 3: Comparison of Wung and New models about 42 homogeneous stack-ups.

No.	Material	Thickness (mm)	Error, e - Wung Model			Error, e - New Model		
			Average	Σe^2	St. Dev.	Average	Σe^2	St. Dev.
1	DQ	0.55	9.9%	0.93	21.1%	8.8%	0.46	13.7%
2	440R	1.2	20.9%	1.31	16.3%	11.8%	0.41	8.9%
3	440R	1.4	17.7%	1.31	20.0%	8.2%	0.27	8.9%
⋮								
126	980DP	1.2	-11.9%	0.89	17.2%	-12.9%	0.68	13.0%
128	590DP	1	0.0%	0.14	8.3%	-4.6%	0.20	8.7%
129	780DP	1	8.0%	0.61	14.9%	1.1%	0.20	9.7%
130	590TRIP	1.2	12.4%	0.79	14.6%	6.7%	0.48	13.4%
131	DQ	0.7	-12.9%	0.47	7.7%	-9.1%	0.31	8.4%
Average			4.3%	1.63	21.3%	-2.9%	0.70	14.3%

Table 4: Comparison of Wung and New models about 23 heterogeneous stack-ups.

No.	Material 1	Material 2	Error, e - Wung Model			Error, e - New Model		
			Average	Σe^2	St. Dev.	Average	Σe^2	St. Dev.
54	590DP 1.2t	590DP 1.0t	-3.9%	0.32	11.3%	-9.8%	0.45	10.1%
55	780DP 1.2t	340Y 1.5t	4.4%	0.14	7.8%	-3.0%	0.05	4.2%
56	780DP 1.2t	590DP 1.0t	4.0%	0.71	17.4%	-2.6%	0.34	12.1%
⋮								
112	590DP 1.2t	1180TRIP 1.4t	5.9%	0.72	17.5%	0.5%	0.51	15.6%
113	780DP 1.0t	980DP 1.0t	-7.9%	0.29	9.0%	-9.7%	0.43	10.7%
114	980DP 1.2t	590TRIP 1.2t	9.9%	1.35	23.3%	5.6%	1.08	22.0%
115	980DP 1.2t	1180TRIP 1.4t	16.0%	0.98	14.8%	10.9%	0.59	13.2%
116	590TRIP 1.2t	1180TRIP 1.4t	4.3%	16.55	86.6%	-18.3%	5.40	45.9%
Average			**10.2%**	**2.05**	**22.2%**	**3.4%**	**0.90**	**16.4%**

6 Conclusion

In order to predict spot weld failure well by macroscopic analysis, the new spot weld failure model is proposed. The new model considers that there is the interaction between the normal and the bending components since the normal and the bending components have same loading direction and plane. Also, the stress is calculated by dividing the fracture load by plug fracture area, πdt. instead of the interfacial fracture area, $\pi d^2/4$ used in conventional stress based models.

A number of automotive steel sheets for homogeneous and heterogeneous stack-ups are evaluated and analyzed by various spot-weld tests. The hybrid method, the comparison of experimental data and simulation for each test is adopted to extract load components of a coupon test for spot weld failure. The fracture surface for 42 automotive steels are constructed about Wung model and the new model. Both Wung model and the new model describe spot weld failure well, but the new model has desirable error value. For automotive steels, exponents of the new model can be assumed to be unity. Then, the new model becomes simpler, and has only 3 coefficients. A coupon test for heterogeneous stack-up has considerable bending component with normal and bending components due to asymmetric material and the thickness. The new model has better prediction that Wung model.
In order to reduce the huge amount of time and manpower for spot weld fracture test according to a lot of combination of welding parameters such as material, the thickness and the weld size, prediction method of coefficients of spot weld failure models is developed from the regression analysis of the database. It is found that the regression model has significant improvement in error for heterogeneous stack-ups as well as homogeneous stack-ups. Especially, the regression of the new model shows the best accuracy. As a result, it is confirmed that the prediction of coefficients of spot weld failure models is very useful and still accurate, and the new model is defined well to predict the spot weld failure.

7 Literature

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