Rupture Modeling of Spot Welds under Dynamic Loading for Car Crash FE Analysis

Authors

Koushi Kumagai, Seiji Hayashi, Takahiro Ohno

Toyota Motor Corporation, Toyota, Japan

Summary:

The deformed shape obtained from car crash FE analysis without considering the rupture of spot welds does not always match with that of actual test if some of the spot welds rupture during crash test. Therefore, simulating the spot weld rupture and its propagation is important to obtain accurate results from car crash FE analysis. Also, dynamic effects have to be considered while modeling the rupture as spot welds are subjected to dynamic loading in a crash test.

A method to measure the rupture loads of spot welds subjected to dynamic loading with greater accuracy has been developed. Also, a spot weld model to accurately predict these rupture loads has been developed. The developed spot weld model has been validated with a full car crash FE analysis. The results of FE analysis show a good correlation between predicted number and location of ruptured welds and those observed in crash test.

Keywords:

Safety, FEM, Spot welds, Dynamic, Rupture

1 Introduction

Body-In-White structure of a car mainly consists of hundreds of fabricated sheet metal parts joined together by spot welds. Some of these welds may rupture during crash test as the car structure deforms absorbing the crash energy. Therefore, in order to accurately estimate the crash deformation in Finite Element (FE) analysis, it is important to simulate the rupture of spot welds.

A model to simulate the spot weld rupture has been already reported by authors[1] in the past. But it was validated only with static tests without giving any considerations to dynamic effects.

Since the car crash is a dynamic event, spot welds rupture under dynamic loading. It is well known that the rupture loads are higher under dynamic loading compared to static loading due to increased strength of steel materials under dynamic loading. Therefore, a spot weld rupture model must consider this increased strength under dynamic loading.

Lin et al[2] have reported that the inertial forces of specimen and fixture affect the measured dynamic rupture loads. Therefore, it is important to reduce the inertial effects for accurately measuring the dynamic rupture loads of spot welds.

2 Development of instrumentation system

In a dynamic spot weld rupture test, the specimen and fixture between spot weld and force transducer are subjected to inertial forces caused by acceleration. These forces become significant if the mass of specimen and fixture between spot weld and force transducer is large. Since these forces act in the opposite direction of pulling, rupture loads at transducer are underestimated. It is necessary to reduce the effect of inertial forces, although they cannot be avoided completely, to accurately estimate the dynamic rupture loads.

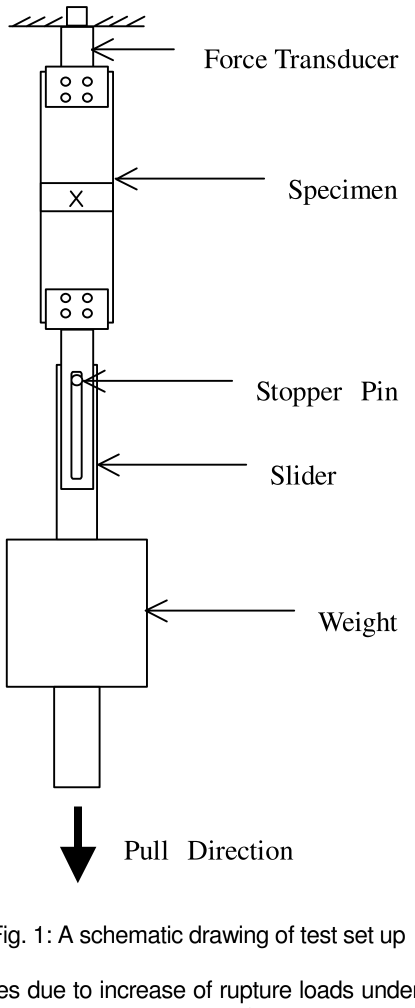

Fig. 1: A schematic drawing of test set up

Also, deformation of specimen increases due to increase of rupture loads under dynamic loading compared to static loading condition. The strain rate effects caused by specimen deformation gets added to the load, making it difficult to accurately estimate the increase in rupture load due to strain rate effects caused by deformation around the spot weld. Therefore, it is necessary to minimize the deformation of specimen so that the increase in rupture load due to strain rate effects caused by deformation of material around the spot weld are accurately estimated.

To reduce the effects due to these issues, following points are considered in designing the specimen and fixture.

(1) The specimen and fixture between spot welds and force transducer are designed to have lightweight to reduce the inertial effects. Furthermore, the rigidity of specimen and fixture are increased to prevent the low frequency

vibrations that affect the spot weld rupture loads and the high frequency vibrations are filtered by low pass filter.
(2) The shape of specimen is designed to prevent the deformation of specimen.

Dynamic load is applied by suddenly stopping an accelerating weight with a stopper pin. The schematic drawing of developed instrumentation system for dynamic spot weld rupture test is shown in Fig. 1.

Coach-peel and lap-shear type of specimens are selected for this study. Specimens are made from 270 and 440 MPa class of steel material with thickness ranging from 0.8mm to 1.6mm. The target rupture speed is 4m/s. Each type of test is repeated for 5 to 10 times. Results of 3 repeated tests in terms of ratio of applied load to average rupture load are shown in Fig. 2. Fig. 2 shows that developed instrumentation system provides high repeatability. These results have smaller effects of inertial forces and specimen deformation because these effects cannot be avoided completely as long as the fixture has some mass and the specimen is deformable.

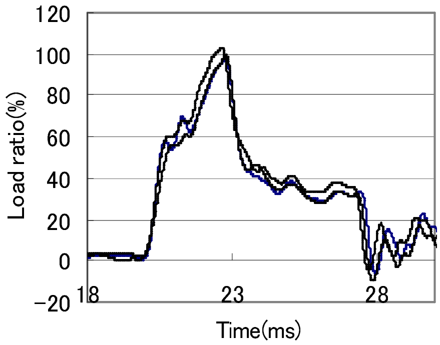

Fig. 2: Time history of spot welds rupture load(270MPa,1.6mm)

3 Development of spot weld model

3.1 Method to identify the dynamic parameters

In this study, the application of spot weld model previously reported by authors[1] has been extended to dynamic loading conditions. A method is developed to identify the dynamic parameters of the model. Identified dynamic parameters are P and C parameters of Cowper-Symonds model incorporated in LS-DYNA.

As the relationship between stress and strain rate is nonlinear, minimum 3 point are needed to identify the parameters. Therefore, dynamic parameters are identified so as to match the rupture loads of static test and two dynamic tests at different velocities in each of coach-peel and lap-shear specimens. Two types of specimens are chosen because the strain rate in lap-shear specimen is higher than that in coach-peel specimen. Since the rupture loads measured at force transducer in test contain the effects of inertial force and specimen deformation, although reduced by instrumentation described in section 2, these effects are taken care in FE model by accurately modeling the specimen, fixture and force transducer used in actual test. Dynamic parameters are identified comparing the FE results with test results.

3.2 Results of dynamic parameters identification

Results of FE analysis used for identification of dynamic parameters of 270 and 440 MPa class of steel are shown in Fig. 3 and 4 respectively. The values plotted in these graphs are the ratios of rupture loads obtained from FE analysis and those obtained from test.

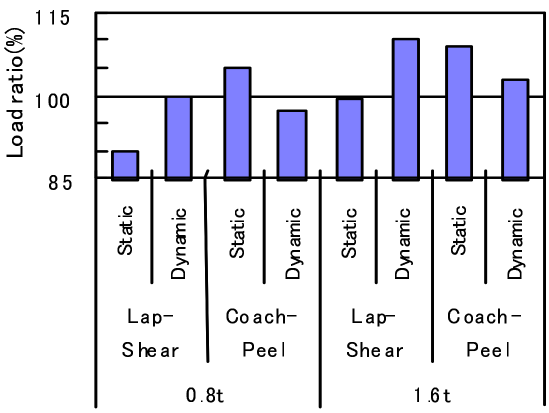

Fig. 3: Comparison of rupture loads (270MPa)

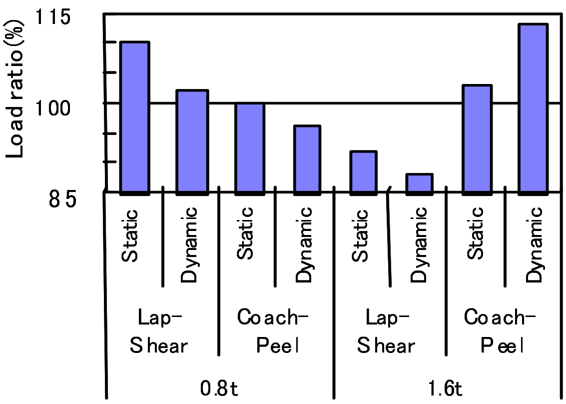

Fig. 4: Comparison of rupture loads (440MPa)

The error in estimation of rupture loads is within 15% as shown in Fig. 3 and 4. Comparison of loading time history between FE analysis and test are shown in Fig. 5 and 6. The load in these plots is normalized with rupture load obtained in test. Fig. 5 shows the loading time history comparison for lap-shear specimen and Fig. 6 shows loading time history comparison for coach-peel specimen. From these figures, it is clear that the loading time history of FE analysis closely matches with that of test till the peak. It is thought that the developed model has good correlation with the dynamic test.

Fig. 7 shows the rupture mode in coach-peel specimen of FE model. The rupture mode in developed spot weld model matches with that observed in tests regardless of thickness, loading rate and loading configuration.

Therefore, the developed spot weld model has good correlation with test under static (as reported earlier[1]) as well as dynamic loading.

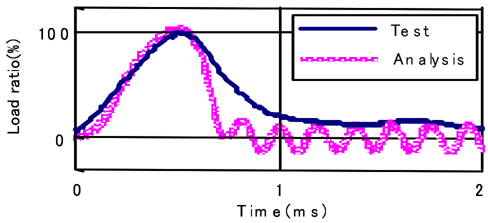

Fig 5: Comparison of loading time history of lap-shear specimen(270Mpa, 0.8mm)

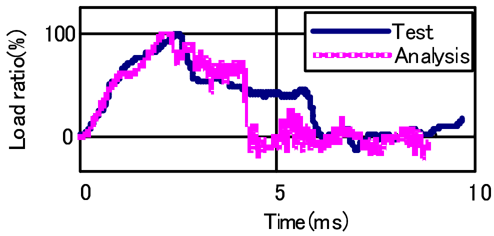

Fig 6: Comparison of loading time history of coach-peel specimen(270Mpa, 0.8mm)

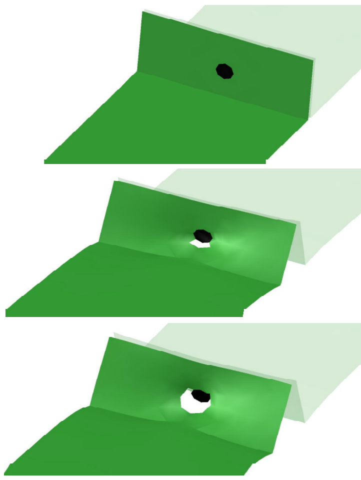

Fig 7: Rupture mode in FE model of coach-peel specimen

4 Validation with full car crash test

4.1 FE model for validation

The accuracy of developed spot weld model has been confirmed with a full car FE analysis. Rear impact analysis according to FMVSS 301 test conditions was carried out. The model used for FE analysis is shown in Fig. 8. About 800 spot welds in the rear part of Body-In-White shown by black dots in Fig. 9 are modeled with the developed spot weld model. The nugget size is set proportional to minimum thickness in the combination of sheets welded together.

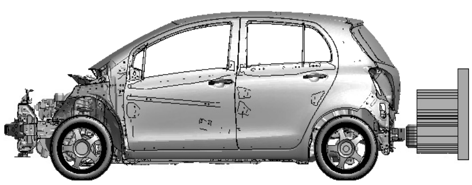

Fig 8: Full car model for rear impact testing

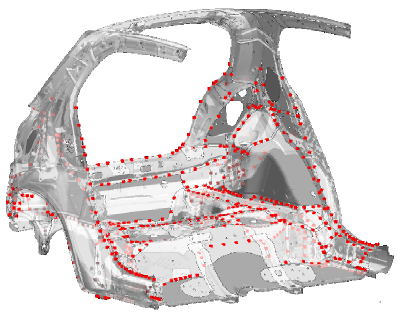

Fig 9: Spot welds modeled with developed spot weld model

4.2 Results of FE analysis

A full car crash analysis of model described in section 4.1 was carried out. The deformed shape is shown in Fig. 10. A comparison of number of ruptured spot welds in test and those predicted by FE analysis is given Table 1. Ruptured spot welds in test are counted based on visual observations. Table 1 shows that the number of ruptured spot welds predicted by FE analysis correlates with the test results. Although the number of ruptured spot welds in FE analysis is little more than that in test as shown in table 1, it is thought that the number of ruptured spot welds in FE analysis correlate with the test results considering the nugget size of spot welds is minimum and the accuracy of spot welds rupture model is within ±15%.

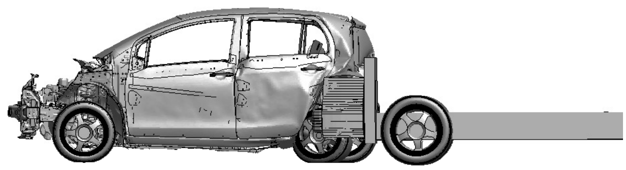

Fig 10: Deformed shape of FE model

Table 1 Comparison of number of ruptured spot welds between test and FE analysis

	Test	Analysis
Number of Ruptured Spot Welds	56	69

Table 2 Comparison of error in estimation of seat anchorage displacement

	without rupture model	with rupture model
Estimation error of seat anchorage displacement	15	4

Table 2 shows the comparison of error in estimation of seat anchorage displacement between FE analysis with and without the developed spot weld model. The estimation error is improved to simulate the spot weld rupture as shown in table 2.

A comparison of number and location of ruptured spot welds is made between FE analysis results and the test results at various locations of the car.

Fig. 11 and 12 show the deformed shape and ruptured spot welds at the left wheel housing in test and in FE analysis respectively. The ruptured spot welds are marked with white circles and alphabets. Each alphabet corresponds to same location of spot weld in both figures. As shown in Fig. 11 and 12, the all locations of ruptured spot welds which are marked from A to J in FE analysis match with those observed in test.

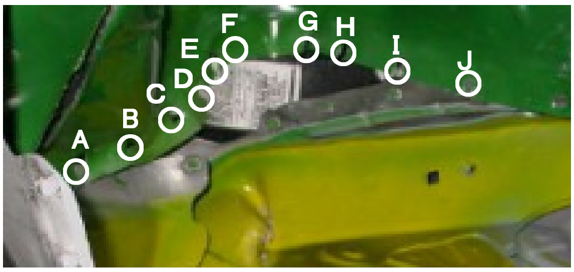

Fig 11: Ruptured spot welds in test (Left wheel housing)

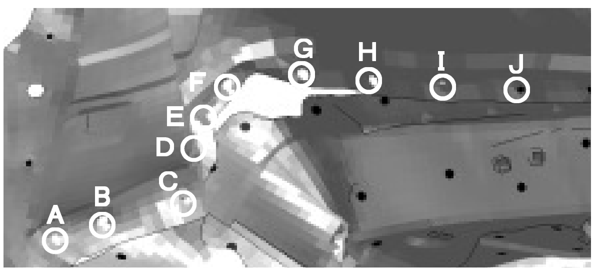

Fig 12: Ruptured spot welds in FE analysis (Left wheel housing)

Fig. 13 and 14 show the deformed shape and ruptured spot welds at the left rear door opening in test and in FE analysis respectively. As shown in these figures, 8 welds have ruptured both in test and FE analysis. Also, the rupture location in FE analysis closely correlates with that in test.

Fig. 15 and 16 show the deformed shape and ruptured spot welds at the right wheel housing in test and in FE analysis respectively. As shown these figures, 6 welds have ruptured in the test, whereas 8 welds have ruptured in FE analysis. Also, the location of some of the ruptured welds in FE analysis does not match with test results.

Fig. 17 and 18 show the deformed shape and ruptured spot welds at the right rear door opening in test and in FE analysis respectively. As shown in these figures, 6 welds have ruptured in the test, whereas 7 welds have ruptured in

FE analysis.

Based on these results it is thought that the developed spot weld model accurately simulates the number and location of ruptured welds in the test.

Fig 13: Ruptured spot welds in test
(Left rear door opening)

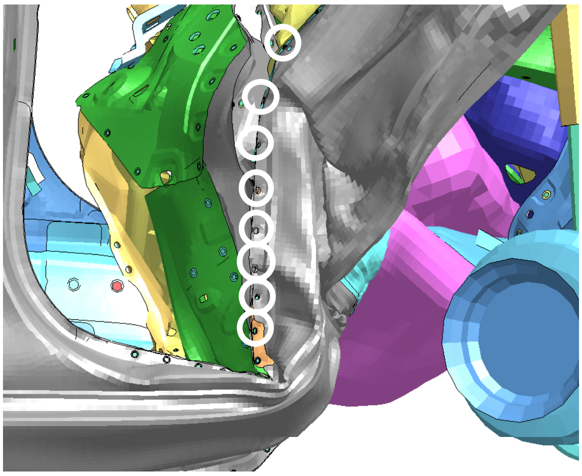

Fig 14: Ruptured spot welds in FE analysis
(Left rear door opening)

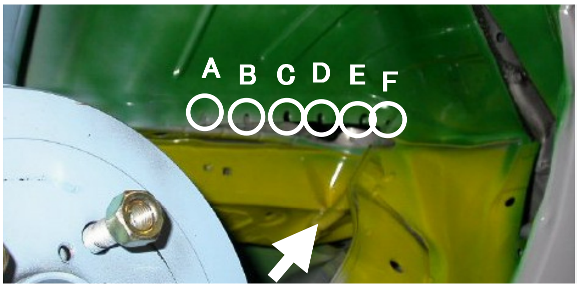

Fig 15: Ruptured spot welds in test
(Right wheel housing)

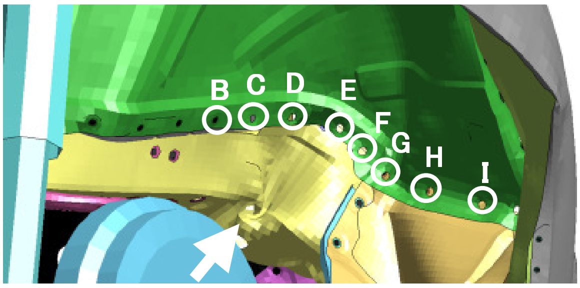

Fig 16: Ruptured spot welds in FE analysis
(Right wheel housing)

Fig 17: Ruptured spot welds in test
(Right rear door opening)

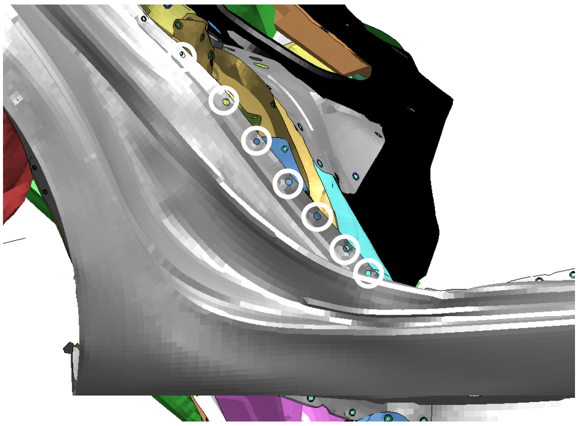

Fig 18: Ruptured spot welds in FE analysis
(Right rear door opening)

5 Discussion

5.1 Spot weld rupture propagation

At left wheel housing, same welds have ruptured in test as well as FE analysis. It is thought that the FE analysis results represent the actual phenomenon at this location.

Therefore it has been chosen for a detailed investigation about the mechanism of rupture propagation using FE analysis results. The ruptured spot welds are marked with alphabets A to J as shown in Fig. 12. At first, weld C ruptures and then the rupture propagates in either direction from C towards A end and J end. The sequence of rupture towards A end is C, B, A and the sequence of rupture towards J end is C, D, E, F, G, H, I, J. Time histories of axial force of few selected welds G, H, I and J are shown in Fig. 19. According to rupture sequence, weld G ruptures first in these selected welds. The axial force of weld G increases first till the critical value and then it starts decreasing gradually due to rupture initiation. When the axial force in weld G starts decreasing, the axial force in weld H start increasing till critical value. This means that the force supported by weld G gets transferred to weld H, which is next to weld G, when the rupture of weld G is initiated. This transfer of load causes the propagation of rupture from weld G to H. In the same manner the rupture propagates from weld H to I and weld I to J. Therefore it is revealed that spot welds rupture in series due to transfer of load supported by one weld to next weld when the first one ruptures causing a chain reaction.

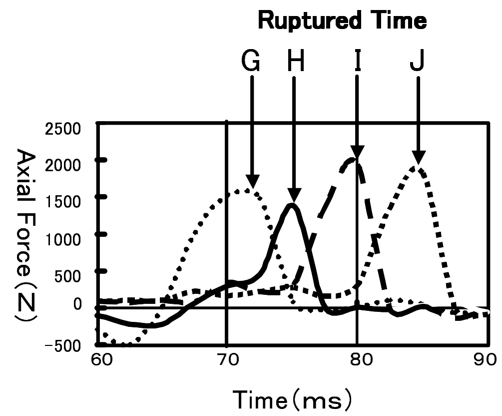

Fig 19: Axial force of ruptured spot welds

5.2 Limitation in prediction of spot weld rupture

The reason for not matching of rupture location at right wheel housing between FE analysis and test as shown in Fig. 15 and 16 has been investigated. Spot welds from A to F rupture in the test but the spot welds from B to I rupture in FE analysis. Although, the difference between number of ruptured welds in FE analysis and test is not much, the location of rupture in FE analysis is different from that in actual test.

The deformed shape in FE analysis and actual test was investigated in detail to find the reason for this difference. It is noticed that the bending location of frame is different in each as shown by arrow mark in Fig. 15 and 16. A closer investigation reveals that, the frame has crushed along longitudinal direction in test. On the contrary, it has bent upward in FE analysis. As the spot welds from A to I connect the frame and wheel housing, it is thought that the difference in location of spot weld rupture is caused by difference in deformation mode of frame. Therefore, it is revealed that the predicted spot weld rupture does not always match with that observed in test if the deformed shape obtained from FE analysis does not match with test deformation because of the reasons other than spot weld rupture.

6 Conclusions

(1) A method of instrumentation to reduce the effects of inertial forces and specimen deformation in dynamic spot weld rupture tests has been developed.
(2) An accurate model for spot weld rupture which correlate well with test results regardless of thickness, loading speed and loading pattern has been developed for 270 and 440 MPa class of steels.
(3) The developed model has been validated with a full car FE analysis. The number and location of ruptured spot welds in FE analysis closely correlate with those observed in actual test.

7 Acknowledgements

The support of Mr. Kumbar Somaling of Trans Cosmos Inc. and Mr. Masahiro Nakagami of Toyota Technical Development Corporation in the validation of spot weld rupture model is greatly appreciated.

8 References

[1] Hayashi, Kumagai: “Development of a seat belt anchorage strength analysis method using dynamic explicit FEM code” JSAE Technical Paper No. 20005511
[2]Lin, Pan, Tyan, Wu, Prasad: “Modeling and Testing of Spot welds under Dynamic Impact Loading Conditions”, SAE Paper 2002-01-0149(2002)