Fatigue Life Prediction of Spot-Weld for Auto Body Based on Multiple Load Cases

Liling Zhang, Qing Jiang, Xuefeng Chen and Xu Wang

Abstract *Objectives*: A typical modern car body (BIW) has about 4,000–6,000 spot welds. It is important for the automotive design engineers to understand the mechanical behavior of different joints and furthermore, to incorporate static, impact, and fatigue strength of these joints using CAE methods. The main failure mode of spot welds for most of applications in a car body is fatigue failure. So, the way to layout the spot welds and predict the fatigue strength distribution in the early design stage of car body development has been one of the most interesting and significant topics in recent years. The main objective of this paper is to suggest multiple load cases considering customers usage for fatigue life prediction of spot-weld for the passenger car in order to improve simulation accuracy and CAE capability in vehicle performance development process. *Methodology and Results*: Loading, geometry and material fatigue properties (SN or EN curve) are three key elements for structural fatigue simulation. During the fatigue life simulation of spot welds in car body, the selection of load cases, the accuracy of welding fatigue SN curves, as well as weld nugget diameter of the selected spot weld and finite element modeling accuracy substantially affect spot weld fatigue damage and life prediction. This paper presents a method for fatigue analysis of spot-weld joints and the evaluation of the group of spot-welds having insufficient fatigue life. The authors focus on finding out more realistic load input condition and spot-welded joint modeling methods in order to conduct structural optimization design by using FEA. A multiple load case analysis process for spot weld fatigue life prediction is developed. Under the multiple load case combining torsion, bump, cornering, braking & accelerating, and by using nCode software, the spot weld fatigue

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analysis is done. As a result, the prediction of weak joints by simulation matches experimental results quite well, applications for several car body design programs conduct good results. *Conclusion and Future Potential Researches*: The advantages and the limitations of the multiple load case analysis method for spot weld fatigue life prediction in auto body design process are discussed. In the literature very few papers are focused on the loading condition improvement. The applications also indicate that current simulation technology is suitable for spot weld fatigue strength distribution prediction, weak spots identification, and A to B comparison in the early design process. However, the correlation analysis between fatigue test results and simulation results should be done. The accuracy of spot weld joint fatigue property (S–N curve) needs to be improved in the future because of the S–N curve significantly affecting the fatigue life and damage calculation.

Keywords Fatigue analysis · Spot weld · Multiple load cases · Auto body

1 Introduction

In modern automobile industry field, the spot weld is applied widely in the manufacture of car body component. The quantities of spot weld in typical car body are between 4,000 and 6,000. The arrangement and number of spot weld directly influence the stiffness, durability and crashworthiness of car body. Because in the practical application the main failure mode of spot weld is fatigue damage, it is significant to further understand the fatigue behavior of spot weld, predict the fatigue life of spot weld in car body in early designing stage and optimize the weak parts of structure, weld quantity and position for shortening research circle and reducing cost of car body.

In recent years, with the rapid development of CAE technology and FEM mathematical theory together with their application, the spot-weld fatigue life could be predicted based on the test data and FEM mathematical simulation. The fatigue damage of spot weld under actual loads conditions could be calculated through the local stresses which are obtained from FEM method according to fatigue life prediction method on spot-weld. This method could support the research and development of automobile engineering. However, in the simulation process of weld spot fatigue life, the simulation results of fatigue damage and life for spot weld are influenced by the accuracy of loads that car body undertake, the accuracy of S–N curve of spot welded joint material, the choice of weld nugget diameter and the accuracy of FEM model.

The objective of this paper is giving a fatigue analysis method for spot-weld under multiple load cases considering the loading conditions of car body in driving process. It is proved to be reasonable in the durability test.

2 Fatigue Life Simulation on Spot-Weld

2.1 Introduction on Fatigue Life Simulation of Spot-Weld

The loads, stress in structure and material property (S–N or E–N curve) are three critical factors for simulation analysis of structure fatigue. Based on the different objective for spot weld research, there are two main methods to assess spot-weld fatigue life at present. Radaj and Sheppard think that under different structure and loads the weld fatigue life could be assessed by mathematical analysis on local stress around spot weld. That is the weld joint assessment method based on local stress. Rupp et al. give another assessment method based on the spot weld force. The fatigue life of spot weld is simulated by calculating spot weld force and making use of the maximum and minimum stress and loading spectrum.

The simulation method in the software adopted in this paper is similar to the research achievement of Rupp et al. The main process is simulating the spot weld with beam element to connect the shell element on top and bottom sheet. The structural stresses of weld nugget and sheet around are calculated with element forces transferred by beam elements. Then the structural stress of weld nugget and junction plate, in conjunction with the fatigue properties of weld nugget and base material are used in fatigue analysis. The spot weld damage and life distribution could be calculated according to rain flow counting method and Miner damage rule by quasi-static analysis on every calculation point. In recent years, this method is extended and developed. The non-beam elements are allowed to simulate spot weld, which is the "regional contact" connection.

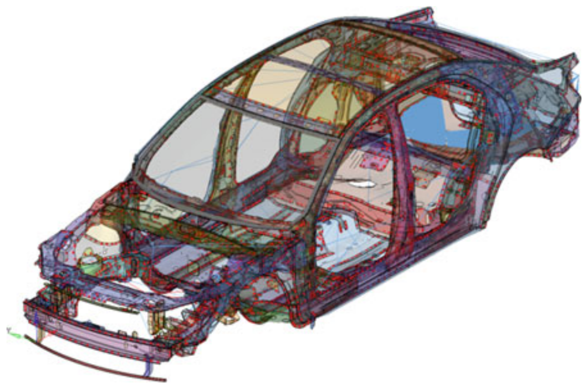
2.2 FEM Model

Figure 1 is the FEM model of some car body which has 4,500 spot welds. The size of element is 10 mm, and the main elements are shell elements. In order to improve the calculation accuracy, the triangle elements should be controlled within 5 % of the total elements.

2.3 Modeling Method for Spot Welds

The modeling methods for spot welds have some distinction according to different fatigue analysis method on spot welds. When the fatigue analysis method on the basis of stress is adopted, good shell elements around spot weld are required. Two different kinds of modeling method for spot welds are shown in Fig. 2. The diameter of washer or weld nugget size is the actual spot-weld size (Fig. 3).

Fig. 1 Body FE model



When using the fatigue analysis method on the basis of weld force, the spot welds could be simulated through rigid beam element, cweld element or acm element. Because this method is to calculate the structural stresses of weld nugget and sheet around through the element forces transfer by beam elements, the accurate transfer of element forces is one of the important conditions which are related to the reasonable result of fatigue analysis. In order to get more accurate analysis result and improve the analysis efficiency, it is necessary to discuss the modeling methods for spot welds.

2.3.1 Beam Element

When the beam element is used to simulate spot weld, the beam elements are required to be vertical to shell elements which are connected by the beam elements. The beam element diameter is the actual weld nugget diameter and beam element should have enough stiffness. Besides, the mesh refinement is not needed for the shell elements around beam element. The experiences indicate that the requirement could be satisfied when the shell elements around spot weld are two times of weld nugget diameter or have the size of about 10 mm. There are two obvious disadvantages for this method in which beam elements are used to present spot weld. On one side, the beam element would cause the stiffness reducing of entire structure, leading to the wrong result in vibration analysis. On the other side, the beam elements are required to be vertical the connected shell elements. So the establishment of model would be a great work when creating the entire car body model, which does not satisfy the requirement of time cost.

2.3.2 ACM Method

ACM method describes spot weld through CHEXA and RBE3 element, as shown in Fig. 4. The nodal force of hexahedral element or MPC force are transformed

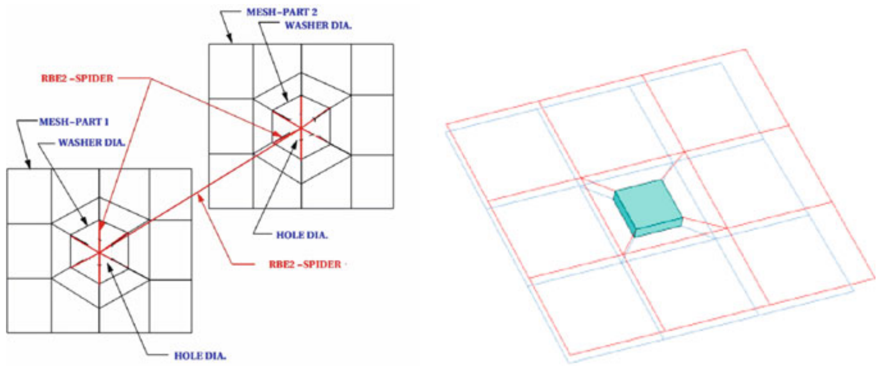


Fig. 2 Two kinds of modeling methods for spot welds

Fig. 3 Spot weld modeled by bar directly connected to nodes of shell element

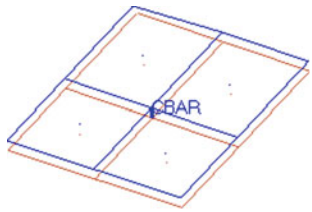
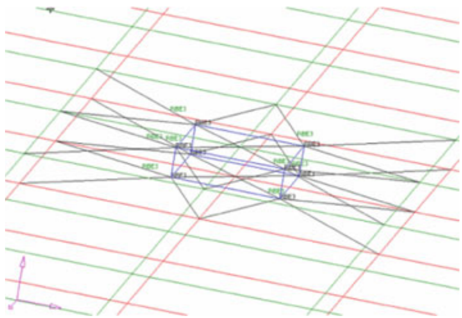


Fig. 4 ACM method of spot weld



into equivalent force and moment of beam element, as shown is Figs. 4 and 5. Then the fatigue analysis is processed by calculating structural stress (Fig. 6).

The advantage of this simulation method is that it is relatively easy to create model and the same elements on top and bottom shell are not needed. The entire structural stiffness is much closer to actual situation. But the uncertainty of regional stiffness for different spot weld might reduce the accordance fatigue life calculation. For example, if some RBE3 elements of two spot weld use the same node, unreasonable calculation result would be caused. If RBE3 element of weld is connected to the edge of shell, the analysis result might be far away from actual result. The connection position where the spot weld connects shell element affects the equivalent force and moment of spot weld obviously and then influences the

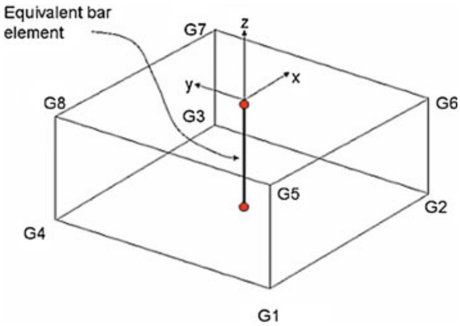


Fig. 5 Hexahedral element and equivalent bar element

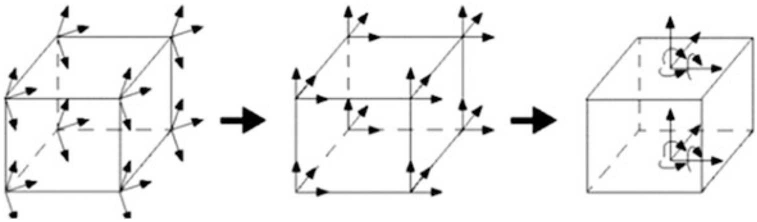


Fig. 6 Forces are transformed from global to local coordinates and then transferred to the centroids of the opposing element faces

result of fatigue life. It is shown according to experiences that the edge of shell element where spot weld exists should keep at least three rows of elements. The RBE3 elements connect to the four corner nodes of the same shell element, as shown in Fig. 7. Based on the characteristic of creating model, relative material properties (S–N curve) are given respectively and then relatively reasonable result could be got. Research shows that more accurate result could be achieved when hexahedron of weld nugget has an angle of 45° with shell element, as shown in Fig. 7b. In this paper, the spot weld is simulated by ACM method.

2.4 The Introduction of Fatigue Analysis on Spot Weld Under Multiple Load Subcases

The vehicle might meet different complicated conditions in driving process which could be separated into some standard subcases including torsion, bump, cornering, braking, accelerating and the combination of these subcases. According to Miner linear damage rule, fatigue is a linear accumulation process of damage and independent with the loading sequence. So the spot-weld fatigue life is calculated under these typical cases of simple constant amplitude cycle equivalent with the

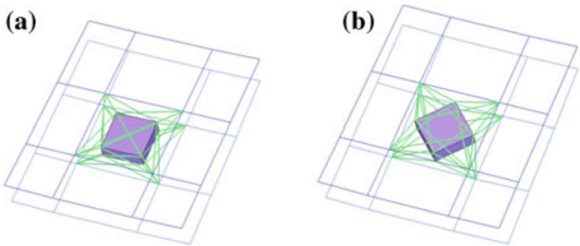


Fig. 7 ACM connection lying within a single element

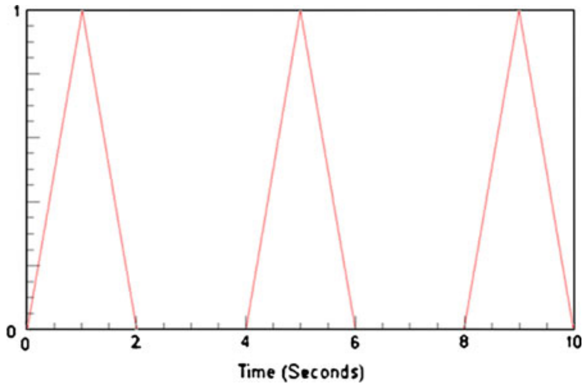


Fig. 8 Simple load data

damage in actual driving conditions in order to predict dangerous fatigued region and point on car.

In calculation, four groups of subcases, which are symmetrical torsion cycle, vertical bump cycle under different amplitude, cornering cycle, accelerating and braking cycle, are building considering the actual loading conditions on car body. Fatigue load spectrum (Fig. 8) in the form of series of half triangular wave or impulse wave is produced by using nCode software. The static analysis result, S–N curve and fatigue load spectrum are used as the input of fatigue analysis. The fatigue life distribution for car body weld under multiple load combination cases could be achieved on the basis of Miner damage rule. The required loads in static analysis are usually got from multi-body dynamic simulation. It should be noticed that the weld nugget and base material have different mechanical properties, and their corresponding S–N curves are also different. The S–N curve of weld nugget is given in Fig. 9.

2.5 Analysis on Fatigue Life of Spot Weld and Test Result

The fatigue life of spot weld is calculated through Design life module in nCode software based on the subcases, materials and S–N curve which are described before. The calculation result indicates that several spot welds where the hat rack

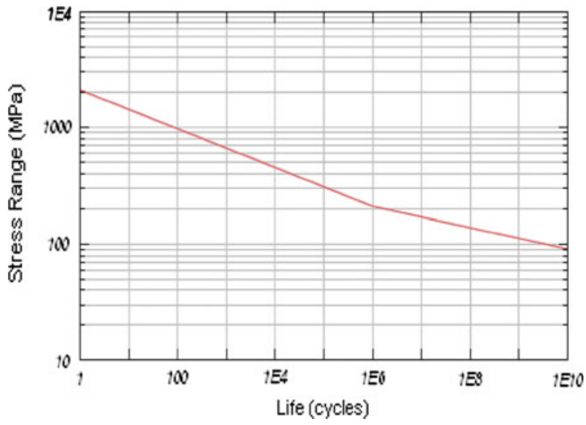
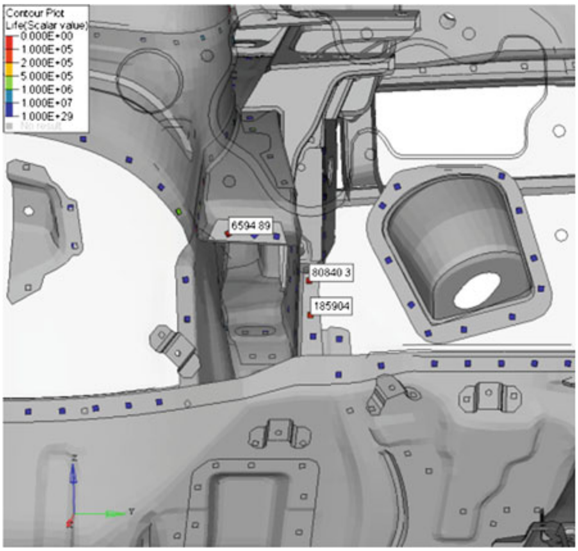


Fig. 9 S–N curve of nugget

Table 1 Spot weld fatigue calculation results with S–N

Spot weld ID	Torsion loadcase		Bump loadcase	
	Life	Damage	Life	Damage
1	6594	1.52e-4	5.9e4	1.69e-5
2	8.08e4	1.24e-5	2.85e5	3.51e-6
3	1.86e5	5.38e-6	1.86e5	5.36e-6
4			2.5e5	4.0e-6

Fig. 10 Spot weld with low fatigue life under vertical bump cycle



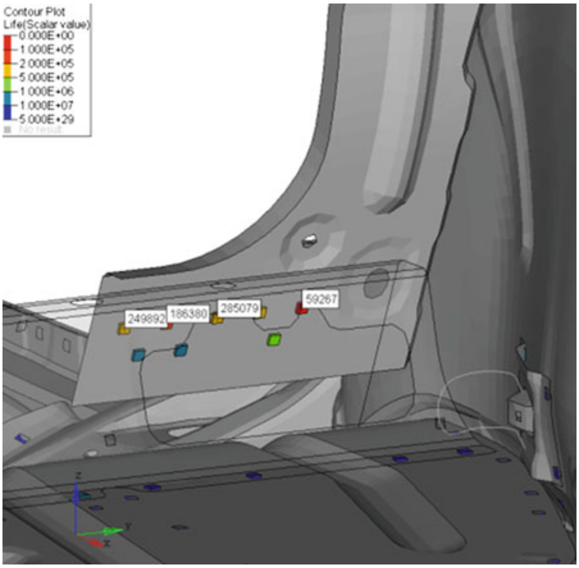


Fig. 11 Spot weld with low fatigue life under symmetrical torsion cycle

plate connects with floor upper beam have relatively low fatigue life under symmetrical torsion cycle. The fatigue life of some spot welds on front wall and front longeron do not satisfy the assessment standard under vertical bump cycle condition. The calculation results are shown in Table 1. In post-processing software The fatigue life and damage distribution of spot welds could be easily identified by different colors, as shown in Figs. 10 and 11. According to the analysis result, modification methods could be taken to the spot weld regions which have high fatigue damage in cooperation with structural designing engineers at the early designing stage in order to eliminate investment risk in advance, reduce the research cost and guarantee the durability requirement.

Figures 12 and 13 give some test photos which are taken in processing of durability test for prototype vehicles on comprehensive road. In the durability test, it was found that different degrees of crack appeared in the spot weld regions which just have low fatigue life in simulation result. It further indicates the prediction way for spot weld fatigue life is reasonable in early designing stage of car body by multiple load cases method.

3 Conclusions

In this paper, the multi-load standard fatigue subcases are used to predict fatigue life of spot weld on car body through FEM analysis in conjunction with actual supporting loads of car body in driving process. The simulation results are well tested and verified in real durability test for prototype vehicles. So the FEM

Fig. 12 Crack on spot weld of front wall

Fig. 13 Crack on spot weld of hat rack

method described before could be widely applied in the research and development of automobile.

Based on the fatigue life simulation method under multi-load fatigue cases, the dangerous fatigue regions on car body could be predicted relatively accurate before producing prototype vehicles. The investment risk could decrease through structure and spot weld optimization at early designing stage which is very important for shortening the research cycle and reducing research cost.

The current fatigue simulation technology of spot weld is appropriate for prediction of spot weld fatigue strength distribution, weak spot identification, and comparison between program A and B in early designing stage of car body. The accuracy of spot weld S–N curve greatly affects the calculation of fatigue life and damage. So it is necessary to further improve the test accuracy of fatigue property (S–N curve) for spot weld.