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Advanced Technologies for Spot Weld Fracture Prediction in Automotive Steel Sheets

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Abstract

In the crash test of automobile bodies, when spot weld fracture and material fracture occur, the intended energy absorption may not be obtained due to the change of the deformation mode. Therefore, it is required to predict fracture of the spot weld using FEM analysis and take countermeasures in advance. We developed the software that enables us to predict fracture of the spot welded part in conjunction with a general-purpose crash analysis solver. The feature of this software is the prediction of fracture considering the width at which spot weld is subject to load. In addition, we introduced new functions developed to improve prediction accuracy.

1. Introduction

If spot weld fracture or material fracture occurs in an automotive body collision test, the target energy may not be absorbed due to the deformation mode change. In recent years, the use of ultra-high strength steel has spread, causing the design of spot weld to be more difficult than before. Against this backdrop, it is becoming necessary to predict fracturing using an FEM analysis method to take measures in advance. However, since the fracture limit of a spot-weld varies depending on the steel type, thickness, welding conditions, parts shape, load mode, etc., many factors have to be considered. For this reason, it has been difficult to create a prediction model.

In the field of automotive body crash analysis, LS-DYNA®, a general-purpose solver, has been widely used. When a spot-weld is modeled with beam elements using LS-DYNA®, the load to the spot-weld is output as shear force and axial force. As indexes of a spot welded joint strength, tensile shear strength (TSS) and cross tensile strength (CTS) are often used.[1] It appears that the TSS mainly represents the strength in the shear direction, while the CTS mainly represents the strength in the axial direction.

Through the TSS and CTS tests conducted at Nippon Steel & Sumitomo Metal Corporation with variation of the material, spot welding conditions, and test piece width, we evaluated the shear force, axial force, and their resultant force acting on the spot-weld. As a result, the fracture strength would vary along with the change in the test piece width if the material or spot welding conditions were the same. Based on the concept of stress concentration from the test results, the relationship between the stress concentration coefficient shown in **Fig. 1** and the ratio between the nugget diameter and test piece width was considered. This led to the creation of a model capable of predicting fracture based on a single curve, regardless of steel type, thickness, spot welding conditions, test piece width, and load mode (TSS, CTS).[2–4] This was followed by the development of software for spot weld fracture prediction called NSafe™-SPOT, which came with the prediction model as the subroutine program of LS-DYNA®.

NSafe™-SPOT was developed based on the premise of the use on a full vehicle model. Fracture can be accurately predicted even when using a relatively simple modeling method using relatively rough shell elements for members and beam elements for a spot-weld (actually, with an optional function that allows calculation with solid elements). While it is necessary to prepare an enormous volume of input files for several thousand spot welds, pre-software (NSafe™-SPOT Pre) was developed as well to assist the file creation.

The use of NSafe™-SPOT Pre helps users to create fracture criteria reflecting information on steel types, thickness, nugget diameter, and parts shape, which differ for each spot weld. The information on the parts shape refers to the width of each spot weld that bears the load (hereinafter referred to as the "effective width"). Specifically, the effective width means spot weld interval or flange

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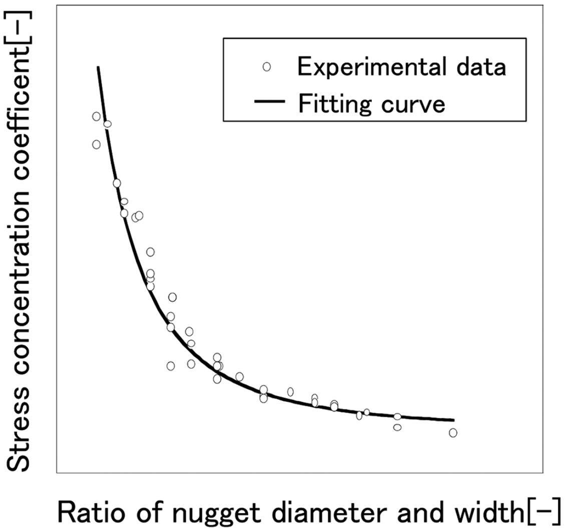

Fig. 1 Relationship between stress concentration coefficient and ratio of nugget diameter and width[2, 3]

width in the direction perpendicular to the loaded direction. (The effective width means the test piece width in a joint test). Compared with other fracture prediction methods, NSafe™-SPOT is characterized by the incorporation of the effective width in the fracture criteria constitutive equation. This allows for predicting fracture in accordance with the shape of the joint surface of actual parts.

Conventionally, NSafe™-SPOT Pre has been capable of reading only the preliminarily-specified value of either the spot welding interval or the flange width. If a parts shape is simple, the software can determine whether the effective width that should be read in the estimated load direction is the spot welding interval or flange. However, in such cases as where the subject of the analysis is a part that consists of multiple components and where the analysis involves the load direction varying during the deformation, the software cannot determine the effective width between the spot welding interval and flange width. This has constituted one of the causes of the low fracture prediction accuracy.

For this reason, we added a feature to NSafe™-SPOT Pre to successively calculate the load direction applied to the spot weld. Furthermore, we added another feature (dynamic effective width function) involving creating an ellipse with two axes of the welding interval and flange width on the spot welding face and defining the diameter of the ellipse perpendicular to the load direction as the effective width, thereby successively changing the effective width according to the load status acting on the spot weld.

2. Dynamic Effective Width Function and Accuracy Verification Method

NSafe™-SPOT creates fracture criteria using the prediction model[2, 3] described above to evaluate the fracture risk by comparing between the shear force and the axial force applied to the spot-weld. The program to dynamically obtain the effective width value according to the load direction necessary to create the criteria is outlined below. Furthermore, using the new features, fracture from the spot-weld in a crash test using actual parts was predicted. The analysis method used in the prediction is explained as well.

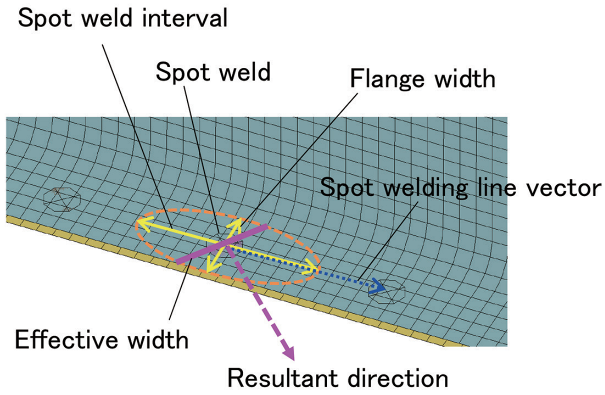

Fig. 2 Example of dynamic effective width

2.1 Overview of the dynamic effective width calculation program

Figure 2 shows a schematic diagram conceptually representing the dynamic effective width function. First, the shell element information comprising the parts is read using functions of NSafe™-SPOT Pre. The same plane is identified based on the angle difference of the normal vector between adjacent shell elements to divide the spot-weld on the same plane into groups. Next, the nearest spot-weld is determined from the spot-weld that belongs to the same group to determine the distance from the nearest spot-weld as the spot welding interval. In addition, the direction of the distance is obtained as the spot welding column vector. Furthermore, the plane width perpendicular to the spot welding column vector is obtained as the flange width. The spot welding interval, flange width, and spot welding column vector thus obtained are written in input files.

After the above procedure, in the process of a crash analysis using LS-DYNA®, NSafe™-SPOT creates an ellipse with two axes of the spot welding interval and the flange width on the flange surface, based on the information contained in the input files and the information on the local coordinates that are set when the spot-weld set with beam elements is converted into solid elements.

Furthermore, the resultant force is calculated from the shear force component and the axial force acting on the spot-welded elements successively calculated during the crash analysis. The resultant force is projected on the flange surface to obtain the direction of the resultant force from the angle difference from the spot welding column vector. The diameter of an ellipse perpendicular to the direction of the resultant force is calculated and is defined as the effective width. For this reason, if the direction of the resultant force successively calculated is changed, the value of the effective width is changed accordingly.

2.2 Accuracy verification method of the fracture prediction model

In order to verify the prediction accuracy of spot welding fracture using the dynamic effective width function, an FEM model was created. The model reproduced the three-point bending test using 1 500-MPa hot stamped steel and a 1.6 mm-thick hat member ($5\sqrt{t}$-diameter nugget [t: sheet thickness], 15 mm-width flange, spot welding interval of 30 mm) shown in **Fig. 3**. An analysis was conducted for a case where the dynamic effective width function was used. At the same time, comparative cases for the conventional function where the effective width was fixed to the spot welding interval and where the effective width was fixed to the flange width were analyzed as well.

3. Accuracy Verification Results of the Fracture Prediction Model

Figure 4 shows photographs of the appearance of the sample taken after the three-point bending test and the fracture prediction results conducted using NSafe™-SPOT. The spot welding fracture position in the test could be accurately predicted with the dynamic effective width function. Contrary to this, the case using the conventional function under the condition of the effective width fixed to the spot welding interval, the predicted number of spot-weld fractures was more than that measured during the test. In the case using the conventional function under the condition of the effective width fixed to the flange width, the spot-weld fracture positions were accurately predicted.

Figures 5 to 7 show the fracture risk at weld point 1 where a spot welding fracture first occurs in the three-point bending test, and at weld point 2 adjacent to weld point 1. When the fracture risk reaches "1", it is regarded as a fracture to delete the spot welding element. The conventional function uses a fixed value as criteria since it assumes the effective width as a fixed value. The dynamic effective width function calculates the fracture risk while varying the criteria since the effective width varies according to the direction of the resultant force. Figure 5 shows the fracture prediction result obtained using the dynamic effective width function. At weld point 1, the input to the spot-weld was increased with a 13 mm-stroke, sharply increasing the fracture risk, but fracture did not occur; fracture occurred with a 30 mm-stroke. At this time, since the input of weld point 2 had already passed its peak to unload weld point 2, fracture did not spread any further.

In contrast, as shown in Fig. 6, under the condition of the conventional function using the effective width fixed to the spot welding interval, the effective width was 30 mm, and the criteria was lower than other conditions. Due to this, when the fracture risk at weld point 1 reached the criteria at a 10 mm-stroke, a fracture occurred. This was just before the input of weld point 2 reached the peak, resulting in immediate spreading of the fracture. Under the condition of the conventional function using the effective width fixed to the flange width as shown in Fig. 7, the effective width on the back sheet side was 60 mm, and so the criteria were high. At

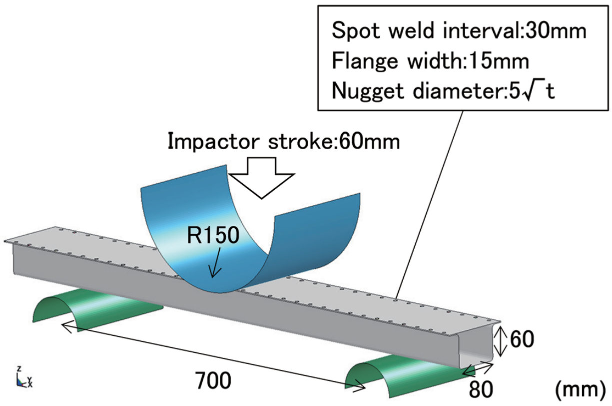

Fig. 3 Three-point bending test condition of hat type member

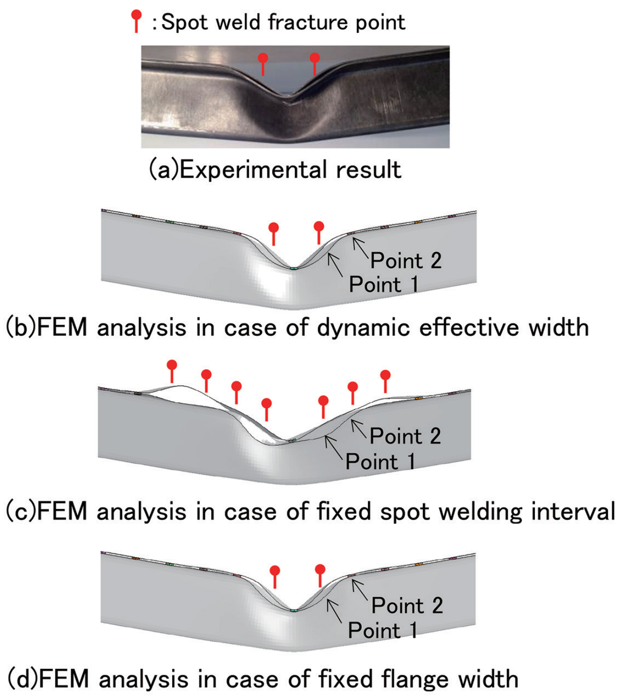

Fig. 4 Comparison of hat member three-point bending test results

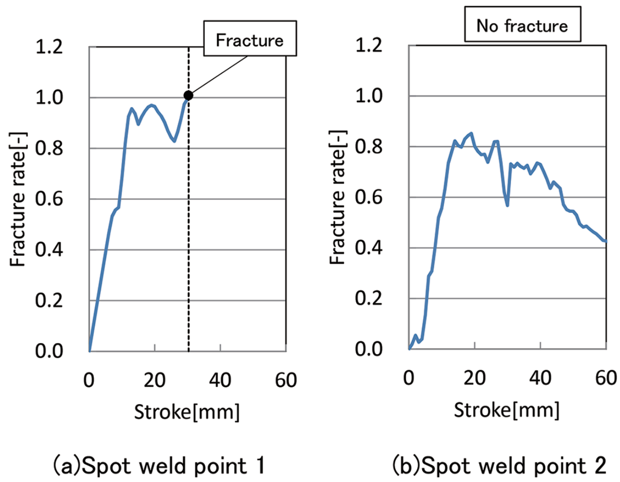

Fig. 5 Fracture prediction results by FEM analysis in case of dynamic effective width

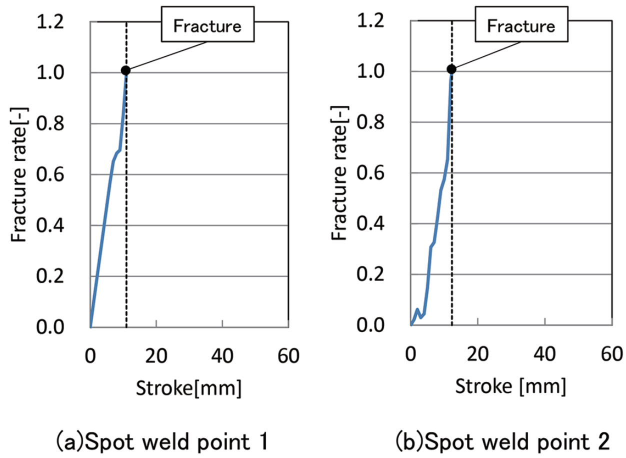

Fig. 6 Fracture prediction results by FEM analysis in case of fixed spot welding interval

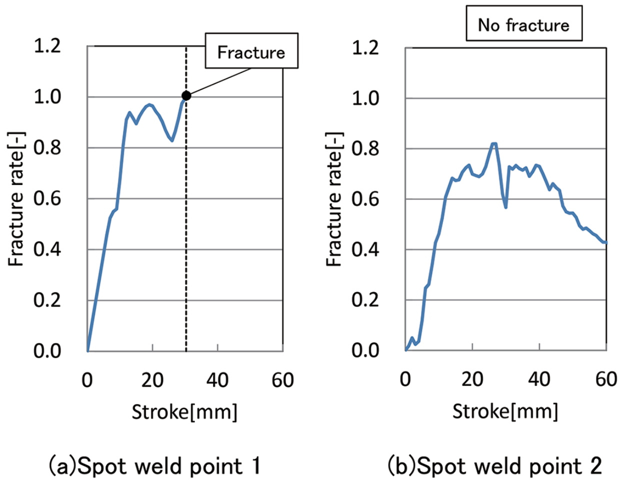

Fig. 7 Fracture prediction results by FEM analysis in case of fixed flange width

weld point 1, fracture did not occur in the input peak at a 13 mm-stroke, but fracture occurred at a 30 mm-stroke. Similar to the case under the dynamic effective width condition, the input of weld point 2 had already passed its peak to unload weld point 2 at this time, preventing the fracture from spreading further.

Figure 8 shows a schematic plan view of the hat member under the dynamic effective condition showing the vector in the resultant force direction applied to the spot-weld at a 30 mm-stroke with which fracture occurred at weld point 1. The resultant force was mostly in the longitudinal direction of the member. The effective width perpendicular to the resultant force direction was automatically selected by the dynamic effective width function. The dynamic effective width function appears to have accurately predicted text results by successively updating the selected effective width according to the change in the resultant force direction. Contrary to this, under the condition of the effective width fixed to the flange width, the resultant force direction of weld point 1 was approximately the longitudinal direction of the member. Since a value close to the appropriate effective width was selected in the end, the high fracture prediction accuracy was obtained. Therefore, if the conditions were changed to cause the resultant force direction change, the prediction accuracy would have been decreased.

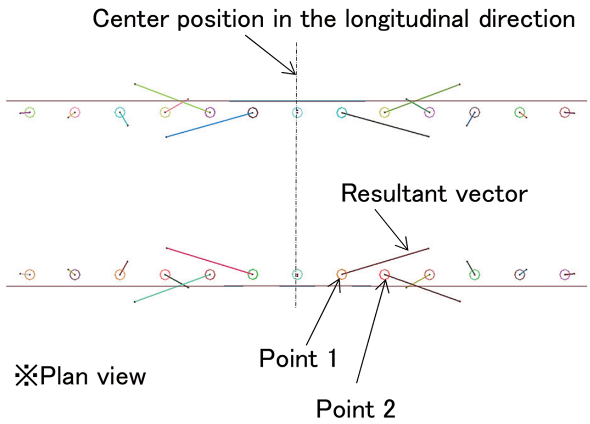

Fig. 8 Resultant vector of each spot weld at the hat member three-point bending test by FEM analysis (30 mm stroke)

4. Conclusion

For automotive full vehicle model crash analysis, software named NSafe™-SPOT capable of accurately predicting fracture starting from a spot-weld has been developed. The most distinctive feature of NSafe™-SPOT is the fracture prediction involving the consideration of the width (effective width) of a spot-weld that bears the load. Recently, a program that dynamically calculates the effective width according to the direction of the load applied to the spot-weld has been developed. Incorporating the new function into the software has allowed fracture from a spot-weld to be predicted more accurately than before in a three-point bending test of the hat member.

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