DYNAMIC FAILURE OF A SPOT WELD IN LAP-SHEAR TESTS UNDER COMBINED LOADING CONDITIONS

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Received 15 June 2008
Revised 23 June 2008

This paper is concerned with the evaluation of the dynamic failure load in the lap-shear tests of a spot weld. Dynamic lap-shear tests of a spot weld in SPRC340R were conducted with different tensile speeds ranging from $5 \times 10^{-3}$ m/sec to 5.0 m/sec. Dynamic effects on the failure load of a spot weld are examined based on the experimental data. Experimental results indicate that failure strength increases with increasing loading rates. Finite element analyses of dynamic lap-shear tests were also performed considering the failure of a spot weld. A spot weld is modeled with a beam element and dynamic failure model is utilized in order to describe the failure of a spot weld in the simulation. The failure loads obtained from the analyses are compared to those from the lap-shear tests. The comparison shows that the failure loads obtained from the analyses are close in consistence with those obtained from the experiments.

Keywords: Resistance spot weld; lap-shear test; dynamic failure load.

1. Introduction

The electric resistance spot welding process is an indispensable assembling process of steel auto-panels in the automotive industries since its introduction in 1950’s. As a modern auto-body contains several thousands of spot welds, the strength of spot welds under impact loading conditions becomes extremely important in the evaluation of the crashworthiness of auto-body members.¹

Usually, the failure of a spot weld is assumed to be independent of the strain rate in the early design stage so that the failure behavior of a spot weld is obtained using static failure tests.²⁻⁴ However, under rapid collapse in a crash situation, the failure behavior of

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a spot weld can be quite different to the statically loaded case. In order to evaluate the dynamic failure load of spot welds, dynamic failure tests have been conducted using the coach-peel specimen and the cross-tension specimen.\(^5\)\(^6\)

With the advancement of computer simulation technology, it is attempted to develop the accurate failure model of a spot weld and implement the failure model into the crash analysis in order to describe the failure of spot welds in vehicle crash simulations. Currently, a common method for modeling a spot weld in the automotive industry is to use a rigid link or a beam element. The onset of failure of a spot weld is determined with the failure model as a function of the forces acting on the spot weld. Song and Huh\(^7\) proposed a dynamic failure model with analyzing experimental results under combined loading conditions since spot welds in auto-body components are subjected to many different types of combined loads when they deform under impact loading conditions.

In this paper, quasi-static and dynamic lap-shear tests were conducted with different tensile speeds ranging from \(5 \times 10^{-5}\) m/sec to 5.0 m/sec. Dynamic effects on the failure load of a spot weld, which is critical for structural crashworthiness, are examined based on the experimental data. FE analyses of lap-shear tests were also performed considering the failure of a spot weld. Dynamic failure model of a spot-weld is utilized to describe the failure of a spot weld in the simulations. The failure loads obtained from the numerical simulation are compared to those from the lap-shear test.

2. Dynamic Lap-Shear Tests of a Spot Weld

2.1. Experimental conditions

Dynamic failure loads of a spot weld in the lap-shear specimens are evaluated in this paper. The spot-welded material was SPRC340R with a thickness of 1.2 mm. Spot welding of the steel sheet was performed using a static spot/projection welding machine. The welding current of 7.6 kA was imposed during the time of 15cycles at 60 Hz with the holding force of 3.0 kN. The diameter of the welded nugget is about 6.5 mm.

In the lap-shear test, a specimen begins to bend and the nugget rotates after the shear load is applied on the spot weld. Such an out-of-plane deformation is induced to eliminate the bending moment in the non-clamping region of the specimen as shown in Fig. 1. Due to the rotation of the nugget, the combined axial and shear loads are applied onto the spot weld in the specimen. As the applied load increases, failure caused by localized necking occurs at one of the localized necking points.

![Fig. 1. Failure mechanism of a spot weld in the lap-shear test.](image-url)
Fig. 2. Dimension of a specimen for dynamic lap-shear tests.

Fig. 3. High speed material testing machine.

Fig. 4. Experimental results for dynamic failure tests of a spot weld: (a) load–displacement curves at various crosshead speeds: (b) effect of the loading rate on the failure load of a spot weld.

Fig. 2 shows schematic description of a specimen used in the dynamic lap-shear test. The specimen is mounted on a high speed material testing machine as shown in Fig. 3 for the dynamic lap-shear test of a spot weld. The high speed material testing machine is servo-hydraulic equipment that has the maximum stroke velocity of 7800 mm/sec and the maximum load of 30 kN. The load is acquired by a piezoelectric-type load cell, Kistler 9051A, and the displacement is obtained by a LDT from Sentech company. In order to achieve the constant velocity during tests, a special jig is used to move to some distance under no loading and then seize a specimen instantly. Using the high speed material testing machine, dynamic lap-shear tests were conducted at the crosshead speeds of 0.1 m/sec, 1.0 m/sec and 5.0 m/sec. Quasi-static test was also performed using the INSTRON 4206 at the crosshead speed of $5 \times 10^{-5}$ m/sec.

2.2. Experimental results

Load–displacement curves of the lap-shear specimens are depicted in Fig. 4(a) at various crosshead speeds. The failure loads of a spot weld are also plotted in the logarithmic scale of the loading rate, as shown in Fig. 4(b). Figures indicate that the failure load increases with increasing crosshead speed while the associated displacement at failure decreases. When the crosshead speed increases from $5 \times 10^{-5}$ m/sec to 5.0 m/sec, the failure load increases from 8.69 kN to 11.06 kN while the displacement at failure
Fig. 5. Deformed shape of the lap-shear specimen: (a) onset of failure; (a) after failure.

Fig. 6. Description of a spot weld in FE analysis: (a) FE modeling; (b) strain-rate dependent failure contour.

decreases from 2.48 mm to 1.09 mm. Fig. 5(a) represents the deformed shapes of the specimen when localized necking occurs. Rotation of the nugget as explained in Fig. 1 is observed from the specimen; thus, the specimen fails under combined axial and shear loads as shown in Fig. 5(b).

3. FE Analysis of Lap-Shear Tests Using the Dynamic Failure Model

Finite element analyses of the lap-shear specimen were also performed considering the failure of a spot weld. The spot weld in the specimen is modeled with a single beam element as shown in Fig. 6(a), which connects a pair of shell elements by constraining all of the degrees of freedom. The mesh size of the shell elements was set to 8 mm, which is widely used in the modeling guide of the auto-body. In order to describe the failure of a spot weld in the simulation, the strain-rate dependent failure contours shown in Fig. 6(b) are considered using the dynamic failure model of a spot weld. The failure model expressed in Eq. (1) was implemented into LS-DYNA3D via a user-subroutine.

\[
\left( \frac{f_x}{F_N} \right)^2 + 1.35 \left( \frac{f_y}{F_N} \right)^2 + \left( \frac{f_z}{F_N} \right)^2 = 1
\]  

(1a)

\[
F_N = 7.96 \left( 1 + 0.00714 \left( \ln \frac{\dot{\varepsilon}}{\varepsilon_{ref}} \right)^{1.49172} \right) \text{kN}
\]  

(1b)

\[
F_x = 12.25 \left( 1 + 0.00714 \left( \ln \frac{\dot{\varepsilon}}{\varepsilon_{ref}} \right)^{1.49172} \right) \text{kN}
\]  

(1c)
Fig. 7. Comparison of the load–displacement curves from the FE analyses and the experiments at various crosshead speeds: (a) $5 \times 10^{-5}$ m/sec; (b) 0.1 m/sec; (c) 1.0 m/sec; (d) 5.0 m/sec.

Table 1. Comparison of the failure load obtained from the FE analyses and the experiments.

<table>
<thead>
<tr>
<th>Crosshead speed (m/sec)</th>
<th>FE Analysis (kN)</th>
<th>Experiment (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5 \times 10^{-5}$</td>
<td>8.80</td>
<td>8.69</td>
</tr>
<tr>
<td>0.1</td>
<td>9.74</td>
<td>9.62</td>
</tr>
<tr>
<td>1.0</td>
<td>10.35</td>
<td>10.23</td>
</tr>
<tr>
<td>5.0</td>
<td>10.92</td>
<td>11.06</td>
</tr>
</tbody>
</table>

Fig. 7 compares load–displacement curves obtained from the analyses to those from the experiments. The failure loads obtained from the analyses and the experiments are summarized in Table 1. The comparison represents that the failure loads of the spot weld obtained from the analyses are close in coincidence with those obtained from the experiments. In the FE analysis, the strain rate of the spot-welded region should be calculated to identify the failure contour of a spot weld. In this paper, the strain rate of the spot weld is calculated from the relative velocity of two nodes in a beam element as shown in Fig. 8(a). Using the calculated strain rates, failure contours at different crosshead speeds are determined from the failure model in Eq. (1). The axial and shear loads acting on the spot weld are also plotted in Fig. 8(b). The graph explains that the shear load is initially applied on the spot weld and that it decreases while the axial load increases due to the rotation of the nugget as the specimen deforms. When the
combination of the forces meets the failure model at each strain rate as shown in Fig. 8(b), the constraint condition imposed on the beam element is released to simulate the failure of the spot weld.

4. Conclusion

Dynamic failure tests of spot-welded lap-shear specimens are conducted at the different tensile speeds ranging from $5 \times 10^{-5} \text{ m/sec}$ to 5.0 m/sec. The failure loads and failure behavior of the specimen are investigated using the experimental results. The results indicate that failure of a spot weld under impact loading condition is quite different to the statically loaded case. In the dynamic loading case, the failure load increases with increasing crosshead speed while the displacement at failure decreases. Finite element analyses of the lap-shear specimen are also performed considering the failure of a spot weld. The dynamic failure model is utilized to describe the failure of a spot weld during the simulation. With the aid of the dynamic failure model, the failure loads obtained from the analyses are close in coincidence with those obtained from the experiments. It can be concluded that dynamic failure model is appropriate to describe the failure behavior of spot welds in vehicle simulations.

References