The Ignored Failure Mode: Spot Weld Under In-Plane Rotation (Finite Element Simulation)

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ABSTRACT

Spot weld failures of complicated structures, such as automobile bodies, are difficult to explain using current multiaxial spot weld failure theory. After introducing the in-plane rotational failure mode, some unexplainable spot weld failures become explainable. The purpose of this report is to introduce the spot weld rotational test, its relative strengths and its finite element simulation. It is found that the strength of a spot weld under the in-plane rotational mode is far below the strengths of the same spot weld under other failure modes such as in-plane shear. Hence, the work conducted in this study could be a foundation for a new generation of multiaxial spot weld failure theory development.

INTRODUCTION

In the field of fracture mechanics, it is well recognized that there are three basic failure modes: opening mode, sliding mode and tearing mode (1,2). These three failure modes have been observed in the spot weld fatigue strength study (3). For instance, the peel mode, compression/ tension mode and the torsion mode of Dieter's work (3) correspond to the opening mode, sliding mode and tearing mode of (1, 2) respectively. Out of these three failure modes, only the opening mode and the sliding modes have been studied for spot weld (4,5,6,7,8 and 9). Publications regarding the tearing mode (or in-plane torsional mode for spot welds) are rare (7,8, 9 and 10).

The rotational mode has typically been ignored in spot weld studies because it has been assumed that in-plane rotational loads are insignificant or non-existent. This assumption has been accepted as common practice in real life industrial applications. For instance, in automobile body structure designs and analyses, sheet metal panels are connected with multiple spot welds. Since the spot weld is small compared to the whole structure, all in-plane twisting loads of spot weld have been converted to the in-plane shearing/stretching loads. Therefore it is assumed that in-plane rotational loads do not exist in spot welds. This observation has been widely accepted as a result of intuitive engineering judgement without serious analytical proof or numerical simulation.

However, in complicated structures, lots of spot weld failures cannot be explained by current multiaxial spot weld failure theory. This leads to the hypothesis that an in-plane rotational failure mode may exist. For instance, in automobile body structure durability tests, the spot welds connecting the shotgun and the hinge pillar were found to fail much earlier than other spot welds (Figure 1). In spite of the fact that these two components use more spot welds than required by current multiaxial failure theory. This early failure phenomenon was replicated by a separate frequency sensitivity study which confirmed that the existence of these spot weld failures were due to design deficiency instead of manufacturing variation. Considering the geometrical shape and the loading conditions, it was found that these spot weld failures could be due to the combination of tensile/shear load and in-plane torsional load. Simplified NASTRAN finite element analyses proved such observation.

PROBLEM DEFINITION

To study the spot weld in-plane deformation, following targets have been set up in this work:

1. design a reproducible test coupon which yields "pure" or "nearly pure" spot weld in-plane failure mode
2. perform the spot weld in-plane rotational test to quantify the spot weld in-plane rotation mechanical responses
3. perform finite element spot weld in-plane rotation simulation to quantify the existence of spot weld in-plane rotational load/deformation relationship and to evaluate the accuracy of finite element results.

COUPON WITH SINGLE SPOT WELD

To start with, a "simple" and "low cost" single spot weld coupon which yields a "nearly pure" and "reproducible" in-plane rotational failure mode was designed and tested (Figure 2a). This coupon contains two pieces of sheet metal which are welded together by a single spot weld at a small angle (< 30°). To prevent the pin from local material compressive failure, the pin hole end was reinforced with a wrapping sheet metal of equal thickness. This wrapping sheet metal was then welded to the main sheet metal with three spot welds as shown in Figure 2b. To prevent the whole test coupon from out-of-plane buckling, a separate guiding plate was used (Figure 2c).

NEARLY PURE IN-PLANE ROTATION TESTS

A. Force and Deflection Curve

The force/deflection curves of single spot weld under in-plane rotation and tensile/shear loads are shown in Figure 3 and 4 respectively. In each figure, curves a1, a2 and a3 represent the results of a spot weld made of 0.92mm/0.92mm, 0.92mm/1.56mm and 1.56mm/1.56mm thickness sheet metals respectively. Comparison of Figure 3 and 4, found that spot welds have a much higher tensile/shear strength than in-plane rotational strength. Comparison of curves Figure 3 curves, found that the shape of a2 is very different from a1 and a3. This is because a2 underwent about twice the rotation of a1 and a3 (a2's rotation was about 150° and a1 and a3's rotation was about 80°). When the rotation angle was close to 180°, the load path was nearly straight. Under such circumstances, the test became a tensile/shear test instead of a rotation test. Therefore, the high peak (rear) portion of a2 was very different from that of a1 and a3.

B. Rotational Deformation

To understand how the rotational deformation was distributed throughout the whole spot weld, straight lines were drawn from the center of a spot weld to the outer edge of the spot weld before testing (Figure 5a). The deformed spot weld is shown in Figure 5c and 5d. In this study, it is found that:

B1. The rotational deformation (Figure 5c and 5d) would occur on both sides of a spot weld when it contained equal thickness of sheet metals.
B2. The rotational deformation (Figure 5c and 5d) would occur only on the thinner side of a spot weld when it contained different thickness of sheet metals.
B3. All the in-plane rotational deformation occurred in HAZ (heat-affect-zone). The straight lines were discontinued or heavily curved in HAZ (Figure 5c and 5d) only. The straight lines in the nugget and base metal all remained straight.

The reasons causing these test phenomenon and the mechanical behavior of the spot weld including the crack initiation and growth were illustrated in (11).

ANALYSIS: FINITE ELEMENT SIMULATION

In this paper, the linear finite element simulation of the spot weld in-plane rotation mechanical behavior were performed. The corresponding nonlinear in-plane rotation mechanical behavior of the spot weld finite element simulation using ABAQUS will be published separately.

A. Single Spot Weld Simulation

The combined MSC NASTRAN CQUAD4, CTRIA3 and CBEAM elements model of a single spot weld for in-plane rotation test is shown in Figure 6. This is the finite element simulation of the test coupon shown on Figure 2. To get a good in-plane rotation of the plate/shell element, the K6ROT parameter were set to 6.24E4 which can yield a 98% in-plane rotational stiffness of the test value.

B. Multiple Spot Weld Simulation

A two pieces connected hypothetical component is analyzed by a MSC NASTRAN model (Figure 7) using two different approaches. The first approach is using RBE2 to simulate the spot weld and the second approach is using CBEAM to simulate the spot weld. The reaction forces of these two approaches are shown in Figure 8.

CONCLUSIONS

As stated in INTRODUCTION of this paper, current common practice (including both design and analysis activities) assumes that spot weld does not have any in-plane rotational load/failure. The factors causing this assumption are the size and the number of spot weld used in a structure. Since lots of small spot weld are used in a large sheet panel structure, people "feel" that any applied in-plane torque will definitely be converted into a "pure" tensile/shear load to each spot weld. Without any rigorous proof, people believe that spot weld in-plane rotational load/failure does not exist and study of such a failure mode is unnecessary. Consequently, any failure criterion based on this assumption will not be able to detect the in-plane rotation dominated spot weld failure.

It is true that spot welds are small compared to the connected panel. However, a spot weld definitely is not a hinged "point" which transfers "force" only. In fact, it is a very complicate load transferring "structure" which transfers force, moment and torque simultaneously. Tests conducted in this study clearly demonstrated the existence and complexity of the in-plane rotational failure mode of spot welds. Furthermore, the finite element examples performed in this work also illustrated the existence of the applied in-plane torque of each spot weld. In certain cases, this in-plane torques could be higher than the tensile/shear load even when multiple spot welds are used.

In addition to the findings stated above, this paper also suggests a reproducible test coupon for physical examination of the spot weld failure and provide an executable finite element technique to simulate the spot weld in-plane rotational deformation. Comparing to the test results, it seems that linear finite element simulation of spot weld using MSC NASTRAN beam element can yield reasonably accurate analytical results for design guidance.

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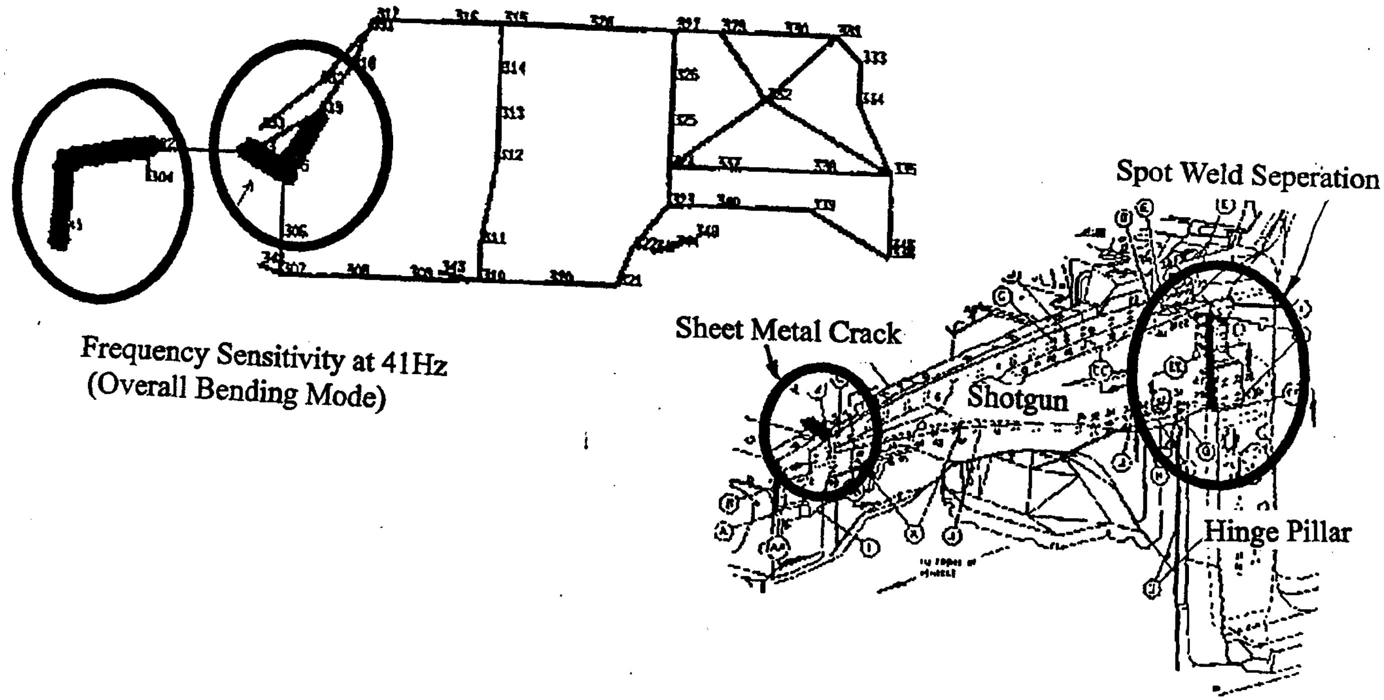


Figure 1 Correlation Between Frequency Sensitivity Study and Durability Tests of a Vehicle Body Structure

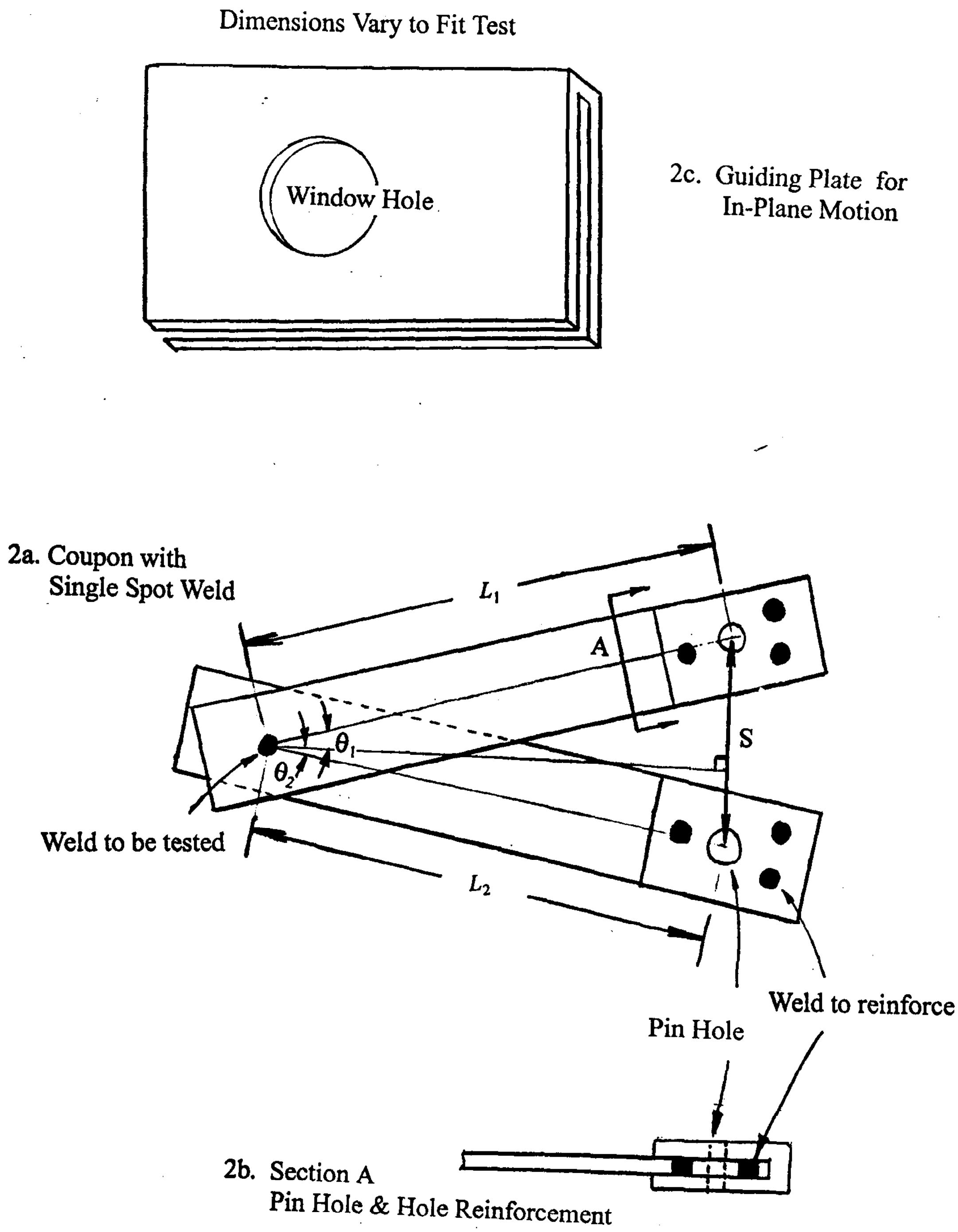


Figure 2 Single Spot Weld Coupon for In-Plane Rotation Test

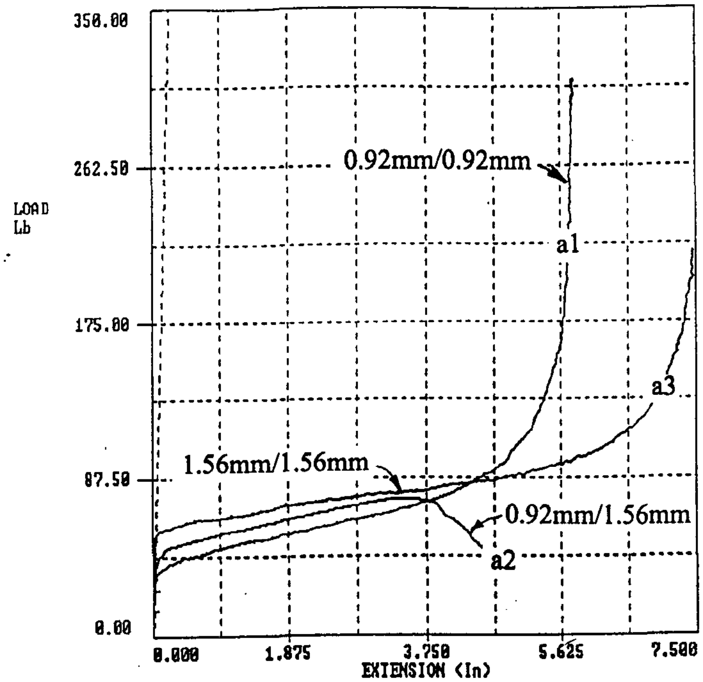


Figure 3 Force/Deflection Curves of Single Spot Welds w/o a Nugget Hole Under In-Plane Rotation Load

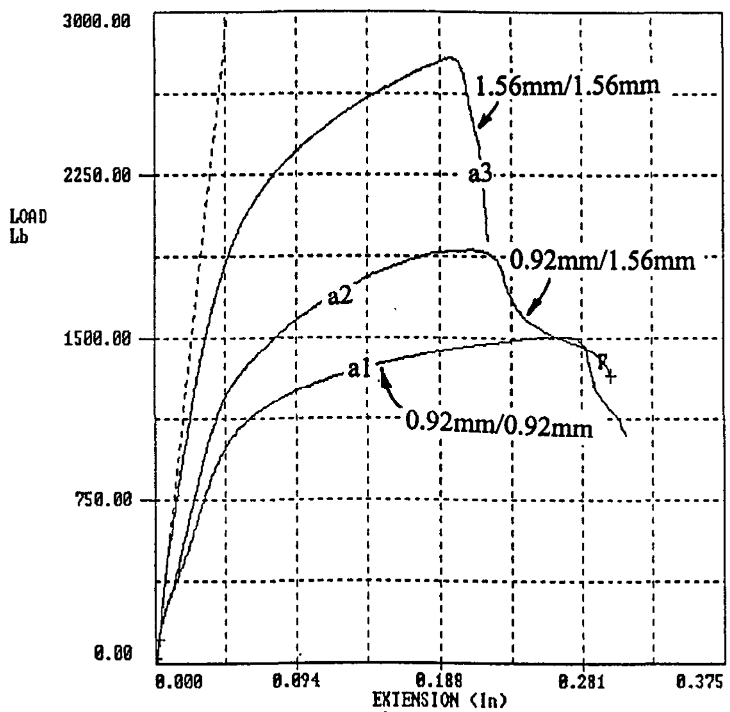


Figure 4 Force/Deflection Curves of Single Spot Welds w/o a Nugget Hole Under In-Plane Tensile/Shear Load

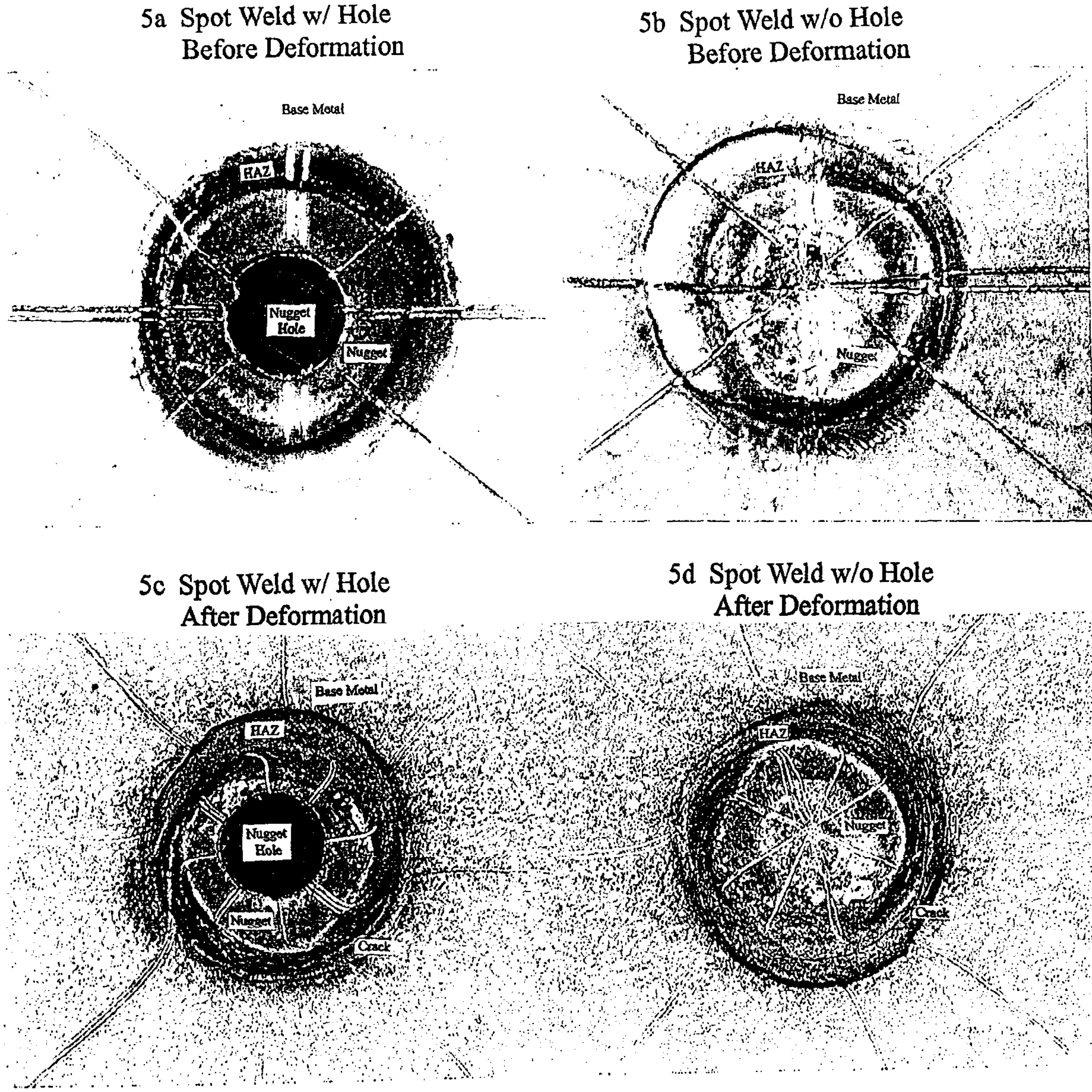


Figure 5 Spot Weld Under Monotonic Rotational Load

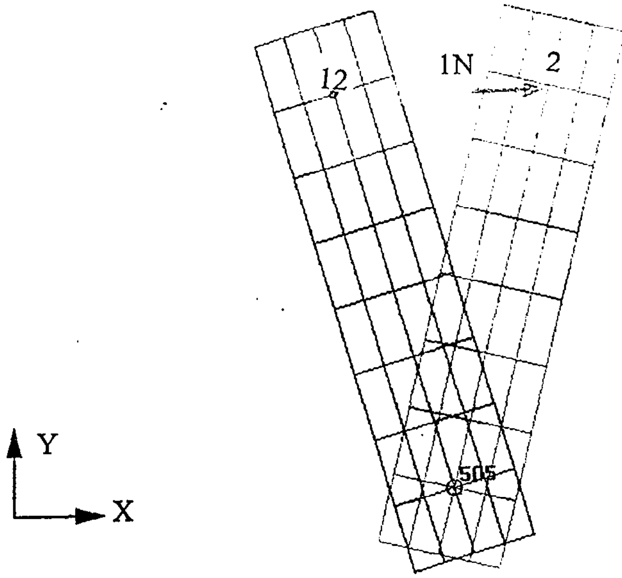


Figure 6 Finite Element Model : Single Spot Weld

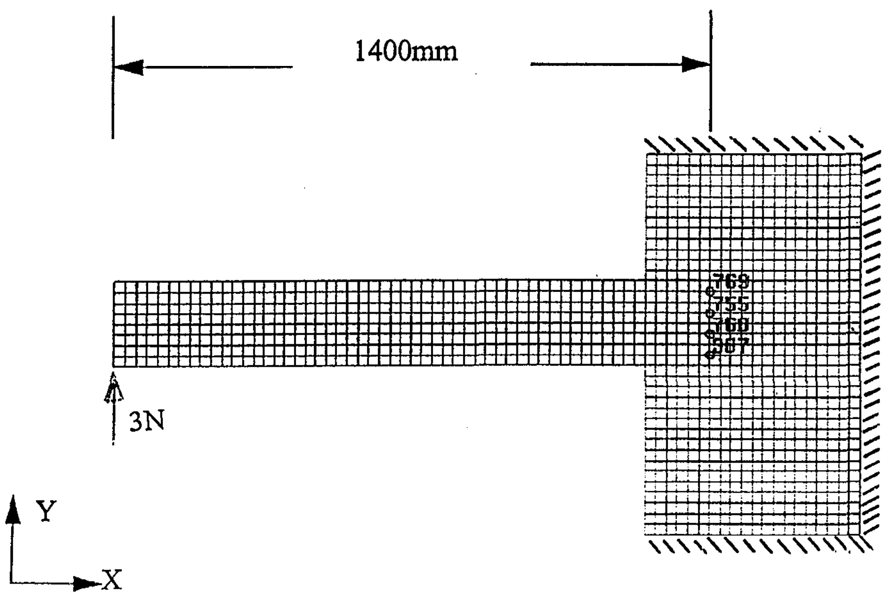
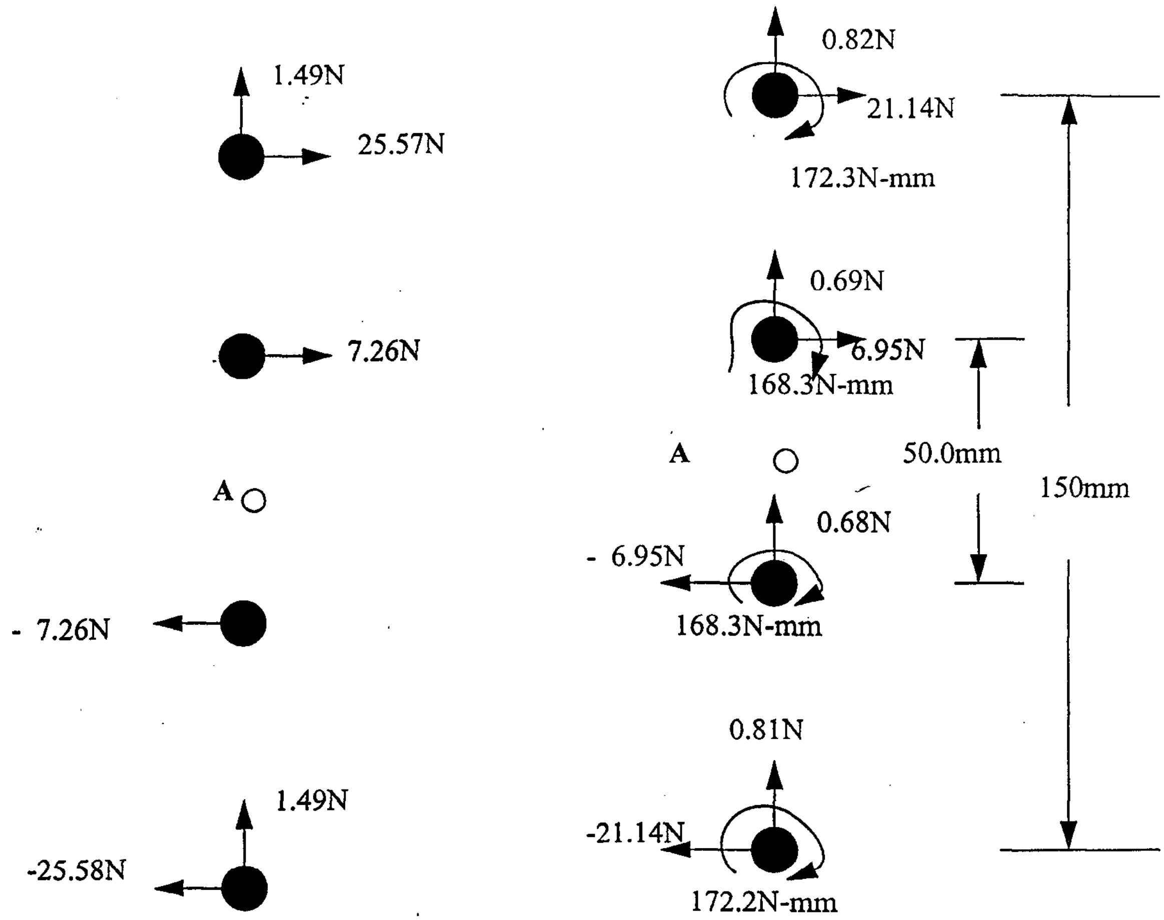


Figure 7 Finite Element Model : Multiple Spot Weld



RBE2 Simulation	CBEAM Simulation
$F_x = 25.57 - 25.58 + 7.26 - 7.26 = 0.0$	$F_x = 21.14 - 6.95 + 6.95 - 21.14 = 0.0$
$F_y = 1.49 + 1.49 = 3$ N	$F_y = 0.82 + 0.69 + 0.68 + 0.81 = 3$ N
$M^A{}_z = 25.58 * 150.0 + 7.26 * 50.0 = 4200.0$ N-mm	$M^A{}_z = 172.3 + 168.3 + 168.3 + 172.2 + 21.14 * 150.0 + 6.95 * 50.0 = 4200.0$ N-mm

Figure 8 Reaction Force Equilibrium Check At Spot Welds