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Dynamic Spot Weld Testing

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EXECUTIVE SUMMARY

Static and dynamic strength tests were performed for spot welded specimens made of dual-phase (DP780) and mild steels (DQSK). Steels were provided by A/SP members and welds were made by RoMan Engineering. Lap-shear (LP) and cross-tension (CT) as well as a newly designed mixed mode specimens were tested using MTS hydraulic universal testing machine for static and drop weight tower for dynamic tests. Three weld nugget sizes for each steel and specimen geometry (LP and CT) were made. In the mixed mode test, only DP780 of one weld size was tested. Load and displacement as functions of time and failure mode of the spot welds were recorded in the tests. Tables 1, 2 and 3 below give a summary of the test.

Table 1 Summary for the static test matrix

Test	*Material*	*Specimen type*	*Number of specimens competed*	*Failure mode*
Static	DP	LS	6	Interfacial (1) Pull-out (5)
	DP	CT	6	Interfacial (2) Pull-out (4)
	DQSK	LS	6	Pull-out (6)
	DQSK	CT	6	Pull-out (6)

Table 2 Summary for the dynamic test matrix

Test	*Material*	*Specimen type*	*Number of specimens competed (loading velocity)*	*Failure mode*
Dynamic	DP	LS	9 (5.6 m/sec) 9 (3.6 m/sec)	Interfacial (2) Pull-out (16)
	DP	CT	10 (5.8 m/sec) 4 (3.6 m/sec) 5 (2.6 m/sec)	Interfacial (3) Pull-out (16)
	DQSK	LS	9 (5.6 m/sec) 9 (3.6 m/sec)	Interfacial (8) Pull-out (10)
	DQSK	CT	8 (5.8 m/sec) 6 (3.6 m/sec) 4 (2.6 m/sec)	Pull-out (18)

Table 3 Summary for the mixed-mode test matrix

Test	*Material*	*Specimen type*	*Number of specimens competed*	*Failure mode*
Static	DP	Mixed	7	Interfacial (5) Pull-out (2)
Dynamic	DP	Mixed	9	Interfacial (6) Pull-out (3)

1. Introduction

Advanced high strength steels (AHSS) have gradually been adopted for auto body construction. In this joint project with Oak Ridge National Laboratory, dynamic and static strength tests for DP780 and mild steels (DQSK) were performed at the University of South Carolina (USC). Lap-shear (LS) and cross tension (CT) specimens with three weld nugget sizes for each specimen geometry were used. The three nugget sizes were selected such that one is smaller, one is equal (medium) and one is larger than the weld nugget size determined from the formula $d = 5\sqrt{t}$, where d is the diameter of the weld nugget and t the thickness of the sheet. In addition, a newly designed mixed mode specimen and fixture were also tested which was made of DP780 with weld nugget size of 5.9 mm, i.e. the large size. Coupons composing the specimens were cut from sheets and all welds were made by RoMan Engineering.

Force versus displacement curves were generated and the failure mode of each specimen was recorded from the tests. The test data are useful in developing a dynamic failure criterion of spot welds made of advanced high strength steels.

This report summarizes the work performed at USC and is composed of introduction (this section), materials and test specimens (section 2), testing program (section 3), test results (section 4), mixed mode test and results (section 5), conclusions (section 6) and appendix (section 7) specifying the specimen label designation. A CD (section 8) is attached with this report which contains all test data in digital form.

2. Materials and Test Specimens

In the first phase of the testing program, two materials (DP780 and DQSK210), two types of specimens (LS and CT), and three nugget sizes (small, medium and large) were tested under static and dynamic loading conditions. Detailed specimen dimensions, materials, and nominal weld nugget size are shown in Table 4.

Figures 1 and 2 show the geometries for the LS and CT specimens, respectively. Each specimen is from two 2 in by 6 in coupons spot welded together. Specimens of DP steel are of 1.15 mm thick and mild steel specimens 1.00 mm thick. The dimensions of the LS and CT follow the ANSI/AWS/SAE/D8.9-97 [1].

Table 4 Specifications for the test specimens

Material	**Specimen Type**	**Dimension (length x width x thickness unit: mm)**	**Nominal Weld Diameter (mm)**
DP780	Lap shear	152 x 51 x 1.15	4.3
DP780	Cross tension	152 x 51 x 1.15	4.3
DP780	Lap shear	152 x 51 x 1.15	5.1
DP780	Cross tension	152 x 51 x 1.15	5.1
DP780	Lap shear	152 x 51 x 1.15	5.9
DP780	Cross tension	152 x 51 x 1.15	5.9
DQSK210	Lap shear	152 x 51 x 1.00	4.0
DQSK210	Cross tension	152 x 51 x 1.00	4.0
DQSK210	Lap shear	152 x 51 x 1.00	4.8
DQSK210	Cross tension	152 x 51 x 1.00	4.8
DQSK210	Lap shear	152 x 51 x 1.00	5.5
DQSK210	Cross tension	152 x 51 x 1.00	5.5

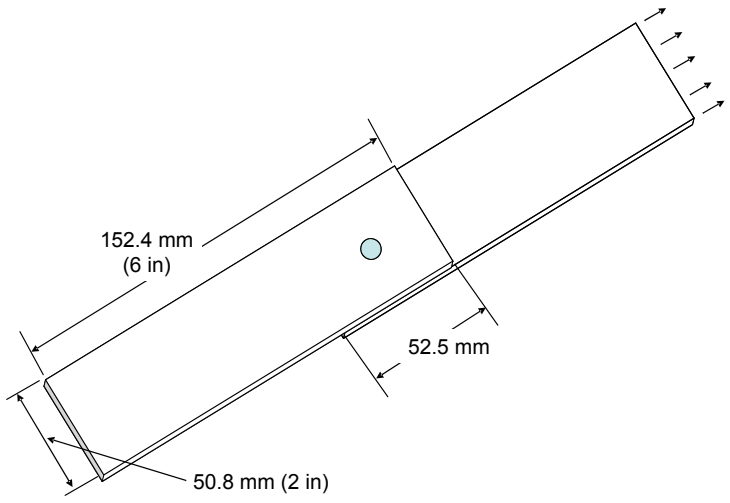


Figure 1 Configuration of lap-shear specimen

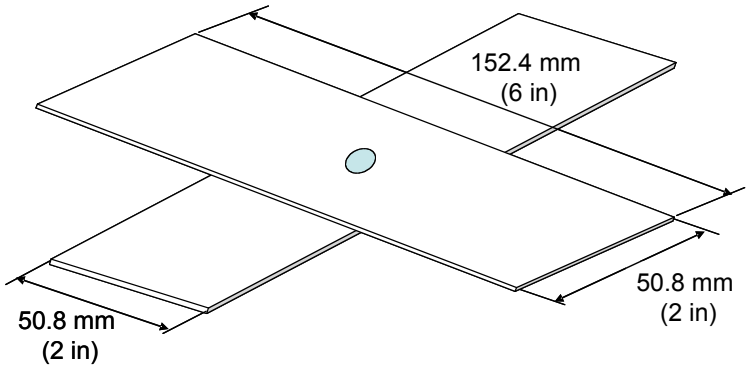


Figure 2 Configuration of cross-tension specimen

3. Testing Programs

The purpose of this test is to generate the load and displacement curves as functions of time for specimens under static and dynamic impact loading conditions. From these data, the strength (i.e. the peak load), energy absorption (from the load-displacement curve), and failure mode of the spot welds can then be determined. The details on each test apparatus are discussed in the following sections.

3.1 Static test

Static tests were conducted using a MTS universal tensile testing system with a displacement rate of 0.001 in/sec. Extensometer was used for the displacement measurement of the LS specimens (Figure 3) and a fixture was used for the CT specimens (Figure 4). The gage length used with the extensometer for all the LS specimens was set at 165 mm, symmetric with respect to the weld nugget. The two clips to the specimen are far away from the weld to avoid any interference from the rotation of the weld nugget region during loading. Machine displacement was used for the CT specimen tests.

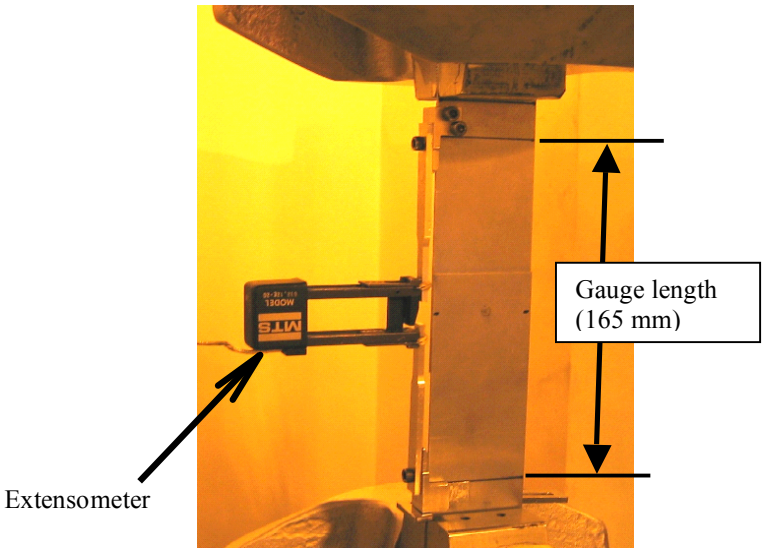
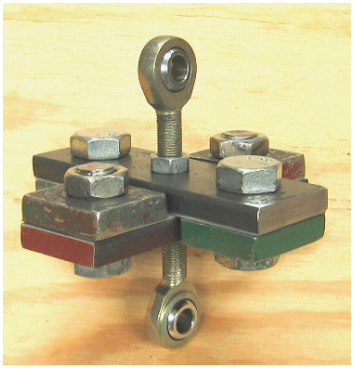


Figure 3 Set-up of lap-shear specimen for the static test



(a)

(b)

Figure 4 Set-up for the static cross-tension specimen test;
(a) test fixture and (b) set-up at MTS machine

3.2 Dynamic test

Dynamic test was conducted using the Instron Drop Weight Tower machine model 8140 (Figure 5). It has a (minimum) drop weight of 225 Kg (496 lbf) and a maximum drop height of 1.60 m (63.5 in). Two piezometric load cells (PCB model 200C20) were used to measure the impact force during the dynamic tests. They are mounted on two sides of the fixture frame used to hold the specimen in place. During the test, symmetric reaction forces were typically found from the two load cells. The resolution of the load cell is 1.3 Newton and the capacity is 90 kN with a frequency response up to 40 KHz. All the channels for data acquisition go through a PCB board (model 483B05), amplifier and signal conditioner. The data were recorded by LabView software with a National Instruments data acquisition board (model: PCI-MIO-16). Dynamic tests for LS and CT specimens were done under three impact velocity; high (5.8 m/sec), medium (3.6 m/sec) and low speed (2.6 m/sec).

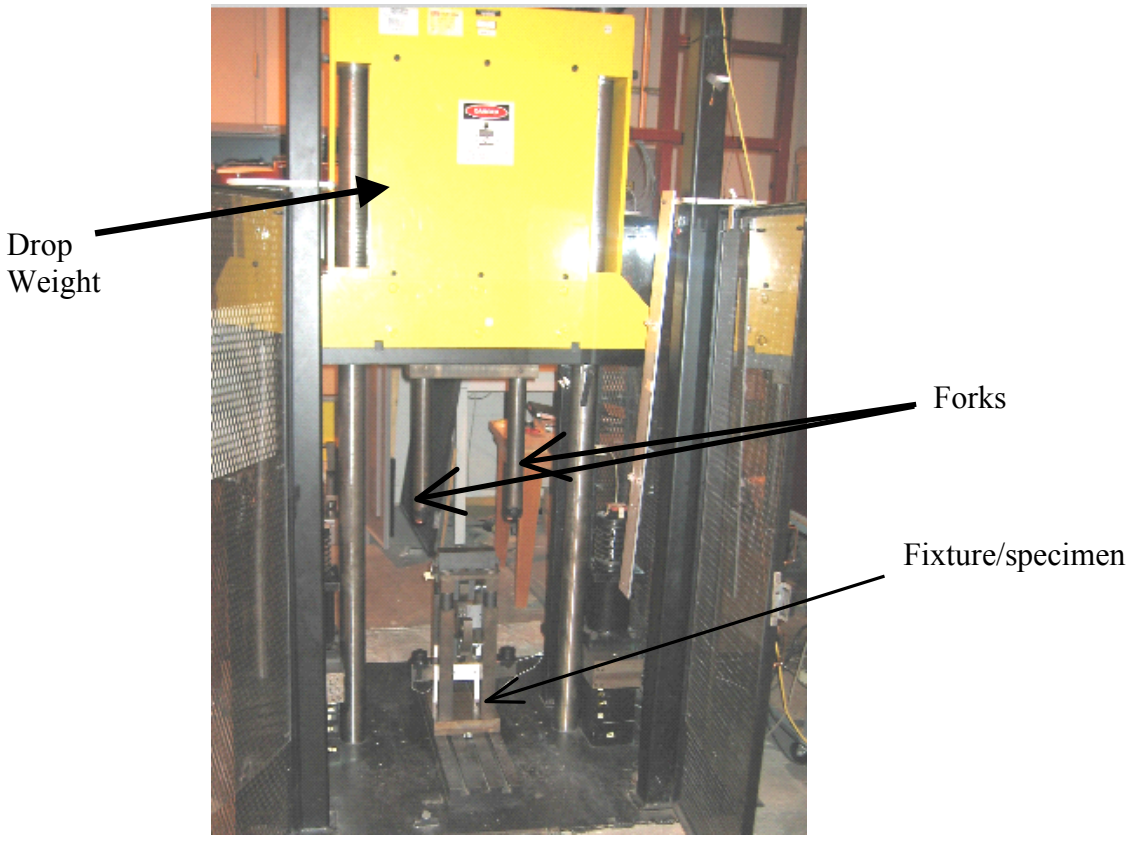


Fig. 5 Instron Drop Weight Tower

During the dynamic impact test the LS specimen is held by the grips that fit into the slots of fixtures (Figure 6). These grips are wedge type to prevent from slipping during the test. The upper fixture is supported by two load cells that measure the reaction forces while the lower fixture is under impact from the forks of the drop weight.

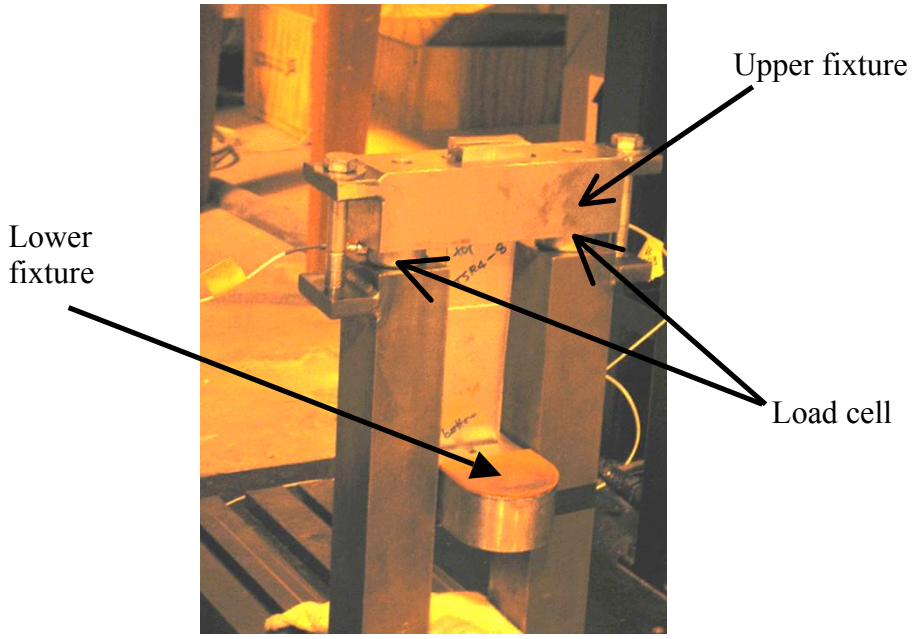


Figure 6 Set-up of lap-shear specimen for the dynamic test

The CT specimen is held by a fixture shown in Figure 7. Two flat heads are under impact load from the forks of the drop weight and the reaction forces are measured from the load cells located under the other two bolted heads.

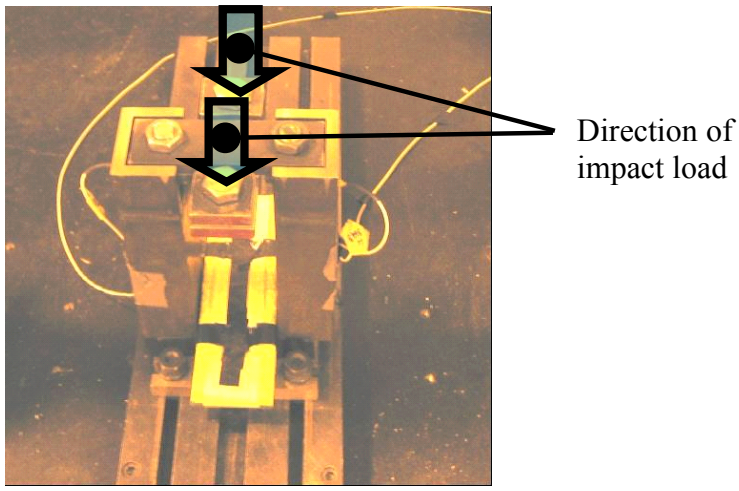


Figure 7 Set-up of cross-tension specimen for the dynamic test

The impact force is obtained from the dynamic load cell installed at the fixture and the displacement is calculated from the drop weight as follows.

From Newton's second law of motion,

$$\sum F = ma \tag{1}$$

where $\sum F$ = vector sum of forces acting on the drop weight

= dead weight – reaction forces measured from the load cells

m = mass of the drop weight

a = acceleration

Once acceleration is known the velocity can be calculated by Equation (2).

$$\int_o^t a dt = \int_o^t dv = v - v_0 \tag{2}$$

where the initial velocity, v_o , is measured when the drop weight passes through a knife edge installed on the drop weight tower machine, right before the forks hit the fixture.

Equation (2) is implemented by a numerical integration scheme (Trapezoidal rule) as

$$\int_{t_1}^{t_n} a dt \approx \sum_{i=1}^{n-1} (t_{i+1} - t_i) \frac{a_{i+1} + a_i}{2} \tag{3}$$

Finally the displacement is

$$\int_o^t v dt = \int_o^t ds = s - s_0 \tag{4}$$

where s is the displacement (or distance) measured from the initial height of the knife edge, s_o.

4. Test Results

4.1 Static Test Results

A summary of results from static tests is shown in Table 5. Actual experimental data and the force versus displacement curves can be found in the CD attached with this report. The designation of specimen/file names are listed in Table A-1 of Appendix. Note there are two specimen numbers for each specimen; i.e. a USC specimen number and a RoMan specimen number (as received). They are marked on each specimen.

Three types of failure modes were identified; i.e. interfacial, pull-out (one side) and pull-out both-sides. Photos of specimens failed in these three modes are provided in Figure 8.

Table 5 Summary for the static test data

Specimen # (RoMan's #)	**Material**	**Dimension (length x width x thickness unit: mm)**	**Nominal Weld Diameter (mm)**	**Max. Strength (Newton)**	**Failure Mode**
DP1CS001 (CTR1-12)	DP780	152 x 51 x 1.15	4.3	5765	Interfacial
DP1CS002 (CTR1-13)	DP780	152 x 51 x 1.15	4.3	6210	Interfacial
DP1LS001 (TSR1-22)	DP780	152 x 51 x 1.15	4.3	13056	Interfacial
DP1LS002 (TSR1-23)	DP780	152 x 51 x 1.15	4.3	13171	Pullout Both-Sides
DP2CS001 (CTR2-12)	DP780	152 x 51 x 1.15	5.1	6555	Pullout
DP2CS002 (CTR2-13)	DP780	152 x 51 x 1.15	5.1	6732	Pullout
DP2LS001 (TSR2-22)	DP780	152 x 51 x 1.15	5.1	14843	Pullout Both-Sides
DP2LS002 (TSR2-23)	DP780	152 x 51 x 1.15	5.1	15226	Pullout Both-Sides
DP3CS001 (CTR3-12)	DP780	152 x 51 x 1.15	5.9	7253	Pullout
DP3CS002 (CTR3-13)	DP780	152 x 51 x 1.15	5.9	7376	Pullout
DP3CS003 (CTR3-14)	DP780	152 x 51 x 1.15	5.9	6954	Pullout
DP3LS001 (TSR3-22)	DP780	152 x 51 x 1.15	5.9	17105	Pullout Both-Sides
DP3LS002 (TSR3-23)	DP780	152 x 51 x 1.15	5.9	17020	Pullout Both-Sides
DQSK1CS001 (CTR4-23)	DQSK	152 x 51 x 1.0	4.0	3212	Pullout

Table 5 continued

Specimen # (RoMan's #)	Material	Dimension (length x width x thickness unit: mm)	Nominal Weld Diameter (mm)	Max. Strength (Newton)	Failure Mode
DQSK1CS002 (CTR4-24)	DQSK	152 x 51 x 1.0	4.0	3419	Pullout
DQSK1LS001 (TSR4-22)	DQSK	152 x 51 x 1.0	4.0	4286	Pullout Both-Sides
DQSK1LS002 (TSR4-23)	DQSK	152 x 51 x 1.0	4.0	4447	Pullout
DQSK2CS001 (CTR5-17)	DQSK	152 x 51 x 1.0	4.8	3419	Pullout
DQSK2CS002 (CTR5-19)	DQSK	152 x 51 x 1.0	4.8	3427	Pullout
DQSK2LS001 (TSR5-22)	DQSK	152 x 51 x 1.0	4.8	4876	Pullout Both-Sides
DQSK2LS002 (TSR5-23)	DQSK	152 x 51 x 1.0	4.8	5029	Pullout Both-Sides
DQSK3CS001 (CTR6-29)	DQSK	152 x 51 x 1.0	5.5	3941	Pullout Both-Sides
DQSK3CS002 (CTR6-30)	DQSK	152 x 51 x 1.0	5.5	4002	Pullout
DQSK3LS001 (TSR6-22)	DQSK	152 x 51 x 1.0	5.5	5888	Pullout Both-Sides
DQSK3LS002 (TSR6-23)	DQSK	152 x 51 x 1.0	5.5	5873	Pullout Both-Sides

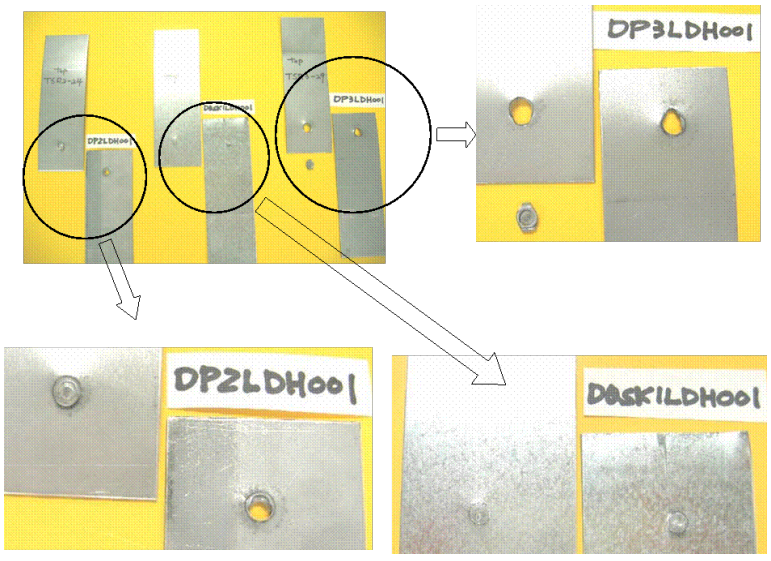


Figure 8 Three distinguished failure modes from the tests; (a) pull-out on both sides,(b) pull-out, and (c) interfacial

The specimen number listed at the first column of Table 5 follows the identification system shown in Figure 9.

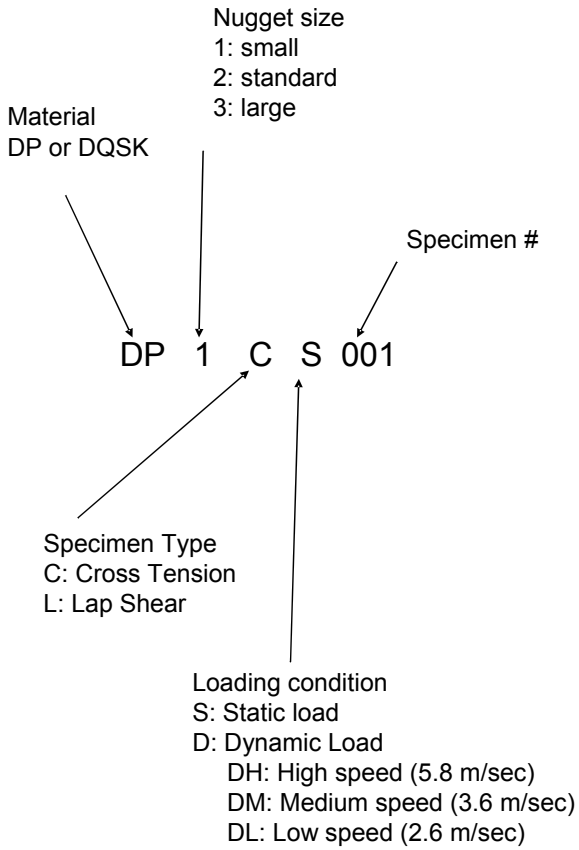


Figure 9 Specimen identification numbering system

Typical load versus displacement curves for the medium sized weld nugget specimens are shown in Figures 10-13.

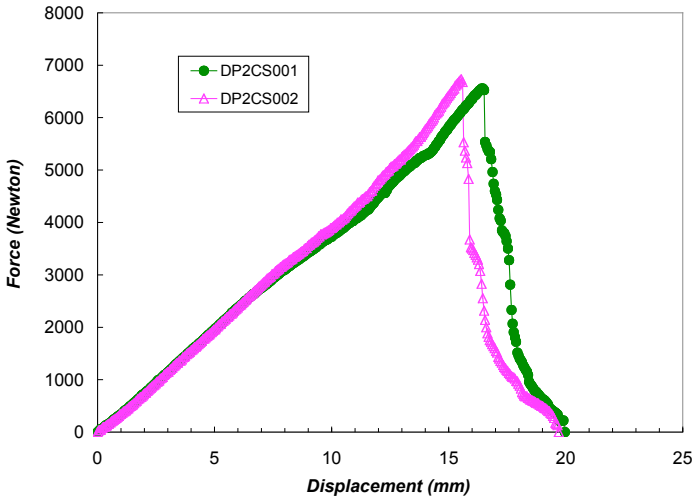


Figure 10 Force versus displacement curves for cross-tension specimens of medium nugget diameter; DP780 under static load

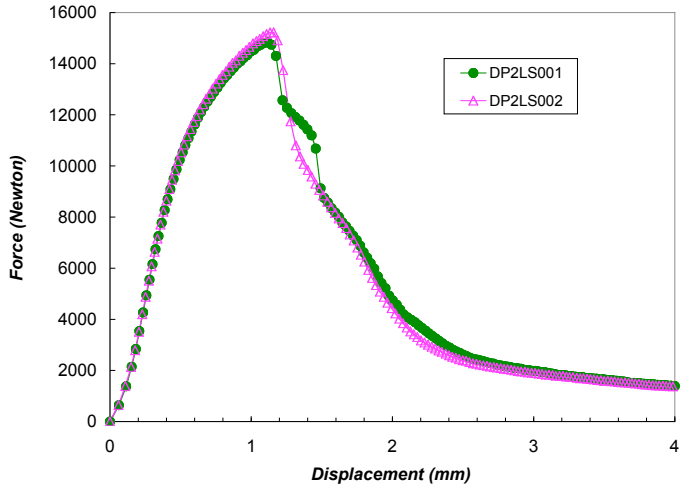


Figure 11 Force versus displacement curves for lap-shear specimens of medium nugget size; DP780 under static load

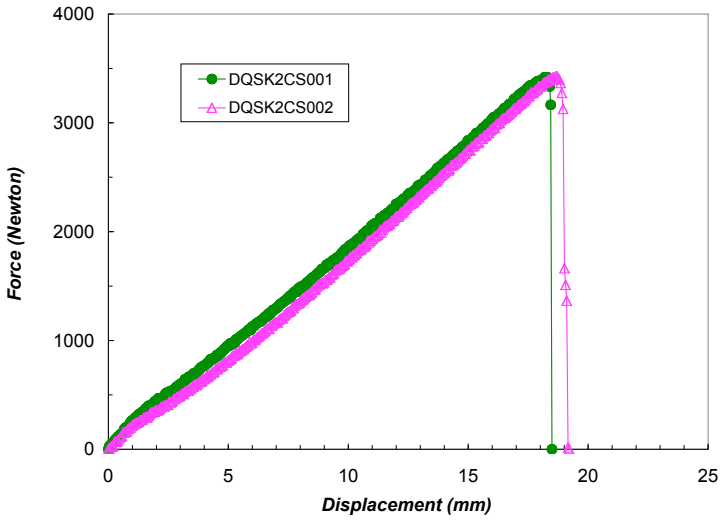


Figure 12 Force versus displacement curves for cross-tension specimens of medium nugget size; mild steel under static load

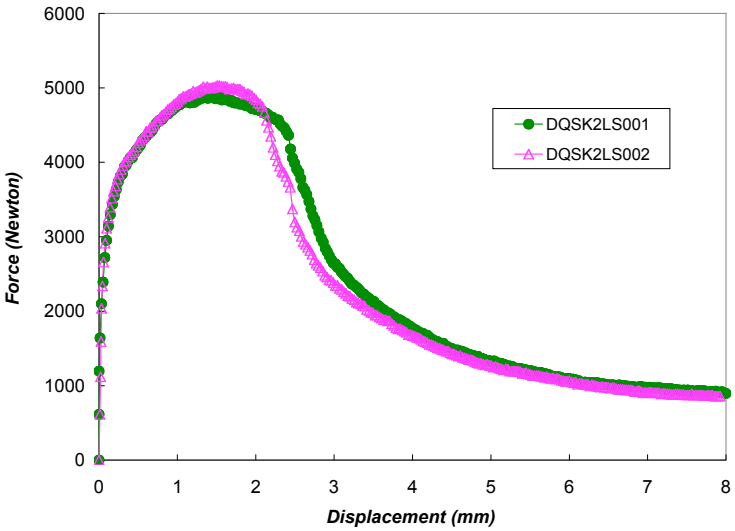


Figure 13 Force versus displacement curves for lap-shear specimens of medium nugget size in mild steel under static load

4.2 Dynamic Test Results

A summary for the results from dynamic tests is shown in Table 6. Actual experimental data and the recorded force versus displacement curves can be found in the CD attached with this report. The file names are listed in Appendix (Table A-2).

Table 6 Summary of the dynamic test data

Specimen # (RoMan's #)	**Material**	**Dimension (length x width x thickness unit: mm)**	**Nominal Weld Diameter (mm)**	**Peak Load (Newton)**	**Failure Mode**
DP1CDH001 (CTR1-16)	DP780	152 x 51 x 1.15	4.3	7329	Interfacial
DP1CDH002 (CTR1-18)	DP780	152 x 51 x 1.15	4.3	7506	Pullout
DP1CDM001 (CTR1-11)	DP780	152 x 51 x 1.15	4.3	6623	Interfacial
DP1CDM002 (CTR1-15)	DP780	152 x 51 x 1.15	4.3	7241	Interfacial
DP1LDH001 (TSR1-25)	DP780	152 x 51 x 1.15	4.3	14023	Pullout
DP1LDH002 (TSR1-26)	DP780	152 x 51 x 1.15	4.3	13089	Pullout Both-Sides
DP1LDH003 (TSR1-21)	DP780	152 x 51 x 1.15	4.3	12921	Interfacial
DP1LDM001 (TSR1-27)	DP780	152 x 51 x 1.15	4.3	13629	Pullout
DP1LDM002 (TSR1-29)	DP780	152 x 51 x 1.15	4.3	12843	Pullout
DP1LDM003 (TSR1-36)	DP780	152 x 51 x 1.15	4.3	13307	Pullout
DP2CDH001 (CTR2-14)	DP780	152 x 51 x 1.15	5.1	8063	Pullout
DP2CDH002 (CTR2-15)	DP780	152 x 51 x 1.15	5.1	9594	Pullout
DP2CDH003 (CTR2-16)	DP780	152 x 51 x 1.15	5.1	8687	Pullout
DP2CDH004 (CTR2-22)	DP780	152 x 51 x 1.15	5.1	8850	Pullout
DP2CDH005 (CTR2-23)	DP780	152 x 51 x 1.15	5.1	9098	Pullout
DP2CDH006 (CTR2-24)	DP780	152 x 51 x 1.15	5.1	8295	Pullout
DP2CDL001 (CTR2-18)	DP780	152 x 51 x 1.15	5.1	8135	Pullout
DP2CDL002 (CTR2-20)	DP780	152 x 51 x 1.15	5.1	8913	Pullout
DP2CDM001 (CTR2-25)	DP780	152 x 51 x 1.15	5.1	8090	Pullout
DP2CDM002 (CTR2-26)	DP780	152 x 51 x 1.15	5.1	8093	Pullout

Table 6 Continued

Specimen # (RoMan's #)	Material	Dimension (length x width x thickness unit: mm)	Nominal Weld Diameter (mm)	Peak Load (Newton)	Fracture Mode
DP2LDH001 (TSR2-24)	DP780	152 x 51 x 1.15	5.1	15641	Pullout
DP2LDH002 (TSR2-25)	DP780	152 x 51 x 1.15	5.1	15696	Pullout Both-Sides
DP2LDH003 (TSR2-28)	DP780	152 x 51 x 1.15	5.1	14914	Interfacial
DP2LDM001 (TSR2-36)	DP780	152 x 51 x 1.15	5.1	16880	Pullout Both-Sides
DP2LDM002 (TSR2-37)	DP780	152 x 51 x 1.15	5.1	14950	Pullout
DP2LDM003 (TSR2-30)	DP780	152 x 51 x 1.15	5.1	15532	Pullout Both-Sides
DP3CDH001 (CTR3-24)	DP780	152 x 51 x 1.15	5.9	10529	Pullout
DP3CDH002 (CTR3-26)	DP780	152 x 51 x 1.15	5.9	10109	Pullout
DP3CDM001 (CTR3-23)	DP780	152 x 51 x 1.15	5.9	8747	Pullout
DP3CDM002 (CTR3-25)	DP780	152 x 51 x 1.15	5.9	10157	Pullout
DP3CDM003 (CTR3-27)	DP780	152 x 51 x 1.15	5.9	8700	Pullout
DP3LDH001 (TSR3-29)	DP780	152 x 51 x 1.15	5.9	18052	Pullout Both-Sides
DP3LDH002 (TSR3-25)	DP780	152 x 51 x 1.15	5.9	17891	Pullout Both-Sides
DP3LDH003 (TSR3-40)	DP780	152 x 51 x 1.15	5.9	17882	Pullout Both-Sides
DP3LDM001 (TSR3-38)	DP780	152 x 51 x 1.15	5.9	17571	Pullout Both-Sides
DP3LDM002 (TSR3-21)	DP780	152 x 51 x 1.15	5.9	19712	Pullout Both-Sides
DP3LDM003 (TSR3-45)	DP780	152 x 51 x 1.15	5.9	18182	Pullout Both-Sides
DQSK1CDH001 (CTR4-38)	DQSK	152 x 51 x 1.0	4.0	3295	Pullout
DQSK1CDH002 (CTR4-5)	DQSK	152 x 51 x 1.0	4.0	3503	Pullout
DQSK1CDL001 (CTR4-37)	DQSK	152 x 51 x 1.0	4.0	3115	Pullout
DQSK1CDL002 (CTR4-6)	DQSK	152 x 51 x 1.0	4.0	3113	Pullout

Table 6 Continued

Specimen # (RoMan's #)	Material	Dimension (length x width x thickness unit: mm)	Nominal Weld Diameter (mm)	Peak Load (Newton)	Fracture Mode
DQSK1LDH001 (TSR4-24)	DQSK	152 x 51 x 1.0	4.0	5017	Interfacial
DQSK1LDH002 (TSR4-25)	DQSK	152 x 51 x 1.0	4.0	5564	Interfacial
DQSK1LDH003 (TSR4-21)	DQSK	152 x 51 x 1.0	4.0	4775	Interfacial
DQSK1LDM001 (TSR4-26)	DQSK	152 x 51 x 1.0	4.0	5359	Interfacial
DQSK1LDM002 (TSR4-27)	DQSK	152 x 51 x 1.0	4.0	4773	Interfacial
DQSK1LDM003 (TSR4-35)	DQSK	152 x 51 x 1.0	4.0	5384	Interfacial
DQSK2CDH001 (CTR5-21)	DQSK	152 x 51 x 1.0	4.8	3526	Pullout
DQSK2CDH002 (CTR5-22)	DQSK	152 x 51 x 1.0	4.8	4376	Pullout
DQSK2CDH003 (CTR5-25)	DQSK	152 x 51 x 1.0	4.8	4134	Pullout
DQSK2CDH004 (CTR5-34)	DQSK	152 x 51 x 1.0	4.8	3625	Pullout
DQSK2CDM001 (CTR5-26)	DQSK	152 x 51 x 1.0	4.8	4800	Pullout
DQSK2CDM002 (CTR5-33)	DQSK	152 x 51 x 1.0	4.8	4172	Pullout
DQSK2CDM003 (CTR5-36)	DQSK	152 x 51 x 1.0	4.8	3554	Pullout
DQSK2LDH001 (TSR5-24)	DQSK	152 x 51 x 1.0	4.8	6127	Pullout
DQSK2LDH002 (TSR5-25)	DQSK	152 x 51 x 1.0	4.8	6020	Pullout
DQSK2LDH003 (TSR5-21)	DQSK	152 x 51 x 1.0	4.8	6021	Interfacial
DQSK2LDM001 (TSR5-26)	DQSK	152 x 51 x 1.0	4.8	6289	Pullout
DQSK2LDM002 (TSR5-27)	DQSK	152 x 51 x 1.0	4.8	6108	Pullout
DQSK2LDM003 (TSR5-46)	DQSK	152 x 51 x 1.0	4.8	5980	Interfacial
DQSK3CDH001 (CTR6-39)	DQSK	152 x 51 x 1.0	5.5	4169	Pullout
DQSK3CDH002 (CTR6-35)	DQSK	152 x 51 x 1.0	5.5	4533	Pullout

Table 6 Continued

Specimen # (RoMan's #)	Material	Dimension (length x width x thickness unit: mm)	Nominal Weld Diameter (mm)	Peal Load (Newton)	Failure Mode
DQSK3CDL001 (CTR6-37)	DQSK	152 x 51 x 1.0	5.5	4362	Pullout
DQSK3CDL002 (CTR6-36)	DQSK	152 x 51 x 1.0	5.5	4483	Pullout
DQSK3CDM001 (CTR6-40)	DQSK	152 x 51 x 1.0	5.5	4207	Pullout
DQSK3CDM002 (CTR6-38)	DQSK	152 x 51 x 1.0	5.5	4396	Pullout
DQSK3LDH001 (TSR6-25)	DQSK	152 x 51 x 1.0	5.5	7225	Pullout
DQSK3LDH002 (TSR6-26)	DQSK	152 x 51 x 1.0	5.5	7916	Pullout
DQSK3LDH003 (TSR6-21)	DQSK	152 x 51 x 1.0	5.5	7336	Pullout
DQSK3LDM001 (TSR6-27)	DQSK	152 x 51 x 1.0	5.5	7358	Pullout
DQSK3LDM002 (TSR6-28)	DQSK	152 x 51 x 1.0	5.5	7448	Pullout
DQSK3LDM003 (TSR6-29)	DQSK	152 x 51 x 1.0	5.5	7088	Pullout

Typical load versus displacement curves for specimens having medium sized weld nugget in DP780 material are shown in Figure 14-17.

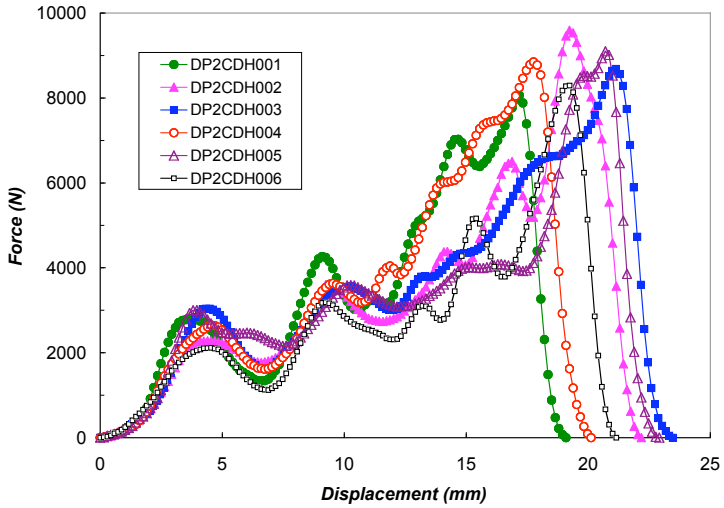


Fig. 14 Force versus displacement; CT specimen under dynamic load (DP780, medium nugget size, high speed impact)

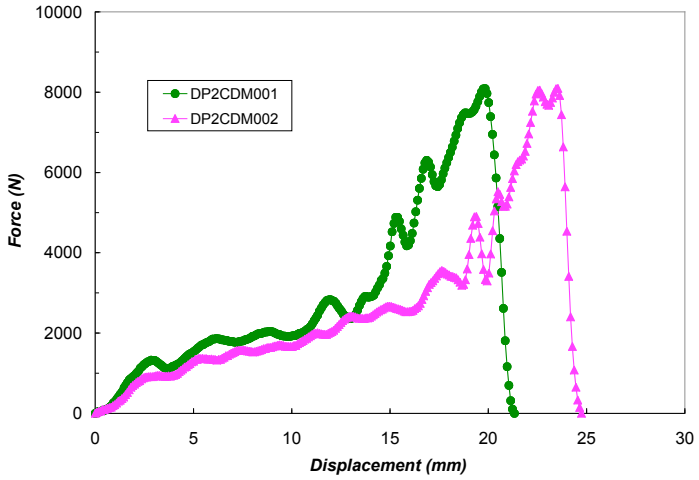


Fig. 15 Force versus displacement; CT specimen under dynamic load (DP780, medium nugget size, medium speed impact)

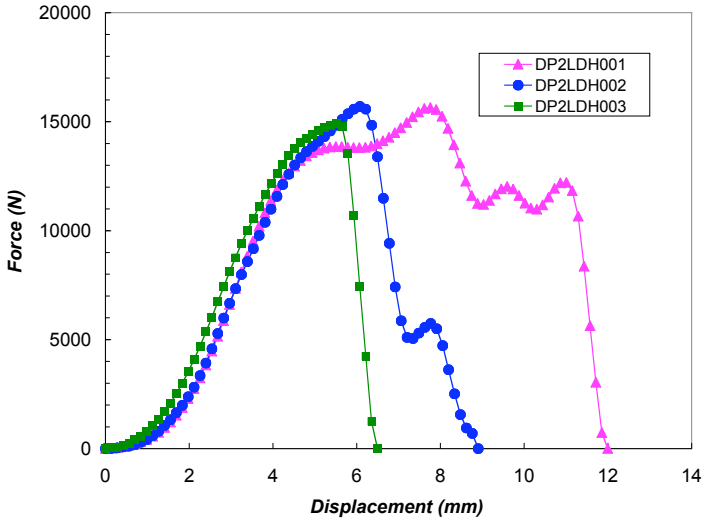


Fig. 16 Force versus displacement; LS specimen under dynamic load (DP780, medium nugget size, high speed impact)

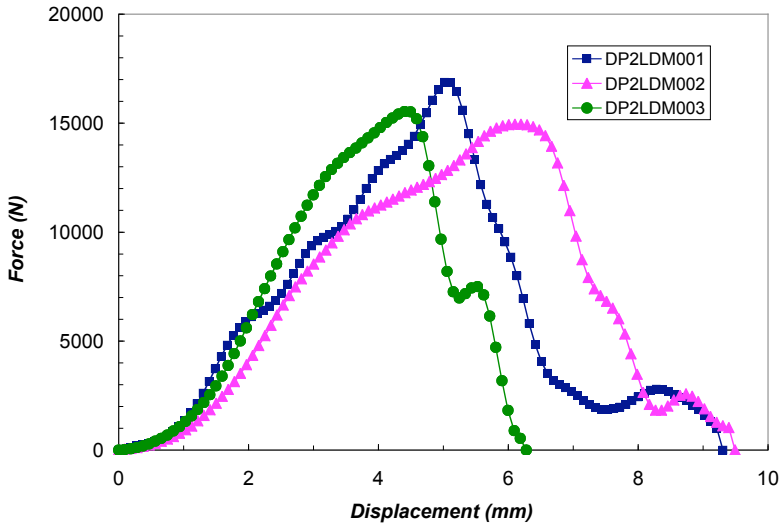


Fig. 17 Force versus displacement; LS specimen under dynamic load (DP780, medium nugget size, medium speed impact)

5. Mixed Mode Test and Results

5.1 Specimen

The geometry and dimensions for the mixed-mode specimens are shown in Figure 18. Static and dynamic tests were performed only for DP780 steel with 1.15 mm thickness and 5.9 mm nugget diameter. The specimen was designed such that a mixed bending, torsion, and tension can be applied to the weld and the load mixity can be varied.

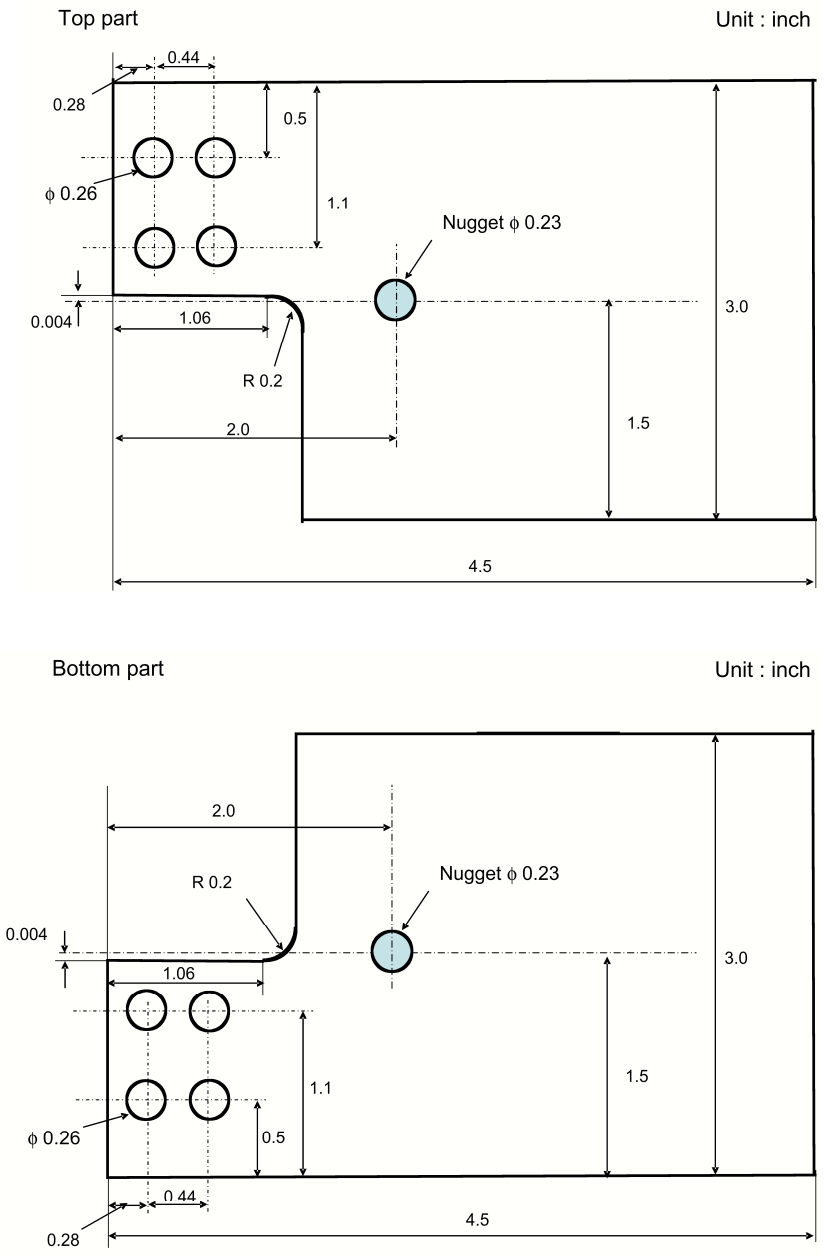


Figure 18 Geometry and dimensions for the mixed-mode specimen (in inches)

5.2 Test Fixture and set up

Static and dynamic tests for mixed-mode specimens were performed by the MTS and Drop Weight Tower Machine, respectively. Various load mixity was achieved by varying the loading angles as shown in Figure 19. Figures 19 and 20 show the set-up for the static and dynamic tests, respectively.

Figure 19 Set-up of mixed-mode fixture for the static test (loading angle, $\theta = 30^{o}$)

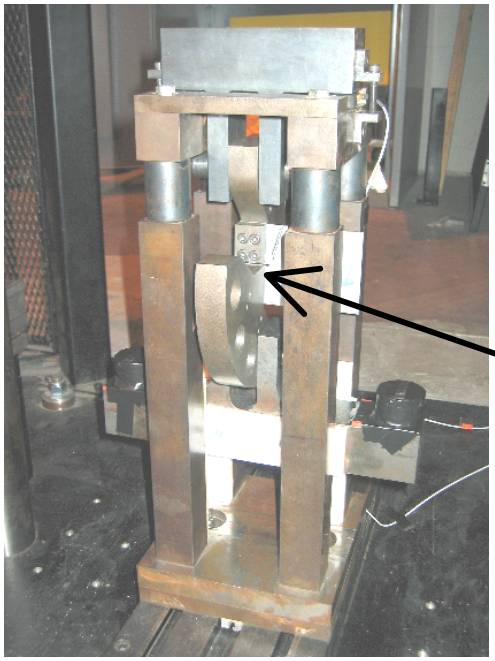


Figure 20 Set-up of mixed-mode fixture for the dynamic test

5.3 Test conditions

Test conditions for the static and dynamic tests are the same as those described in Sections 3.1 and 3.2 for LP and CT specimens, except the fixture. Three loading angles are considered, i.e. 0^o, 30^o and 90^o (Figure 21). The dynamic tests were done only with the impact speed at 5.4 m/sec, which is the highest speed of the drop weight machine. The specimen number listed at the first column of Table 7 follows the identification system shown in Figure 21.

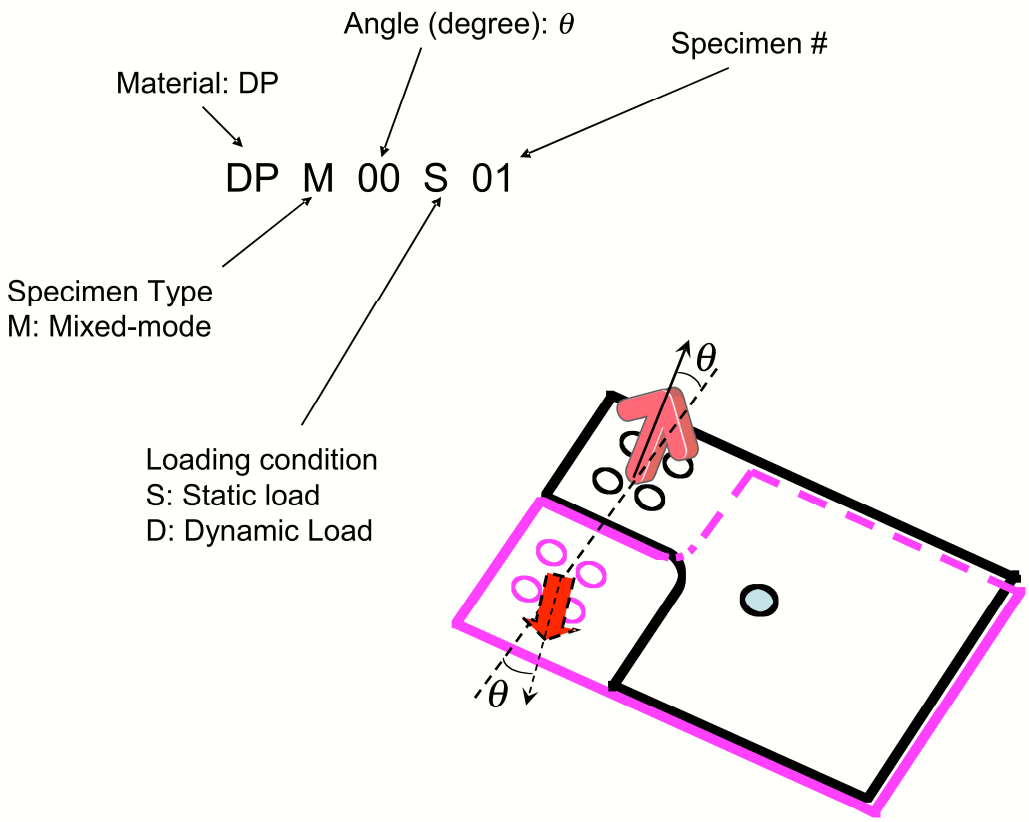


Figure 21 Specimen identification numbers for mixed-mode specimen

5.4. Test Results

A summary of the results from mixed-mode tests is shown in Table 7. Actual experimental data and the force versus displacement curves can be found in the CD attached to this report. The file names are listed in Appendix (Table A-3).

Table 7 Summary for the mixed-mode test data

Specimen # (RoMan's #)	**Material**	**Loading condition**	**Nominal Weld Diameter (mm)**	**Max. Strength (Newton)**	**Fracture Mode**
DPM00S01 (A3)	DP780	static	5.9	9613	Interfacial
DPM00S02 (A6)	DP780	static	5.9	8747	Interfacial
DPM00S03 (A9)	DP780	static	5.9	9345	Interfacial
DPM30S01 (A4)	DP780	static	5.9	2445	Interfacial
DPM30S02 (A7)	DP780	static	5.9	3097	Pull-out
DPM90S01 (A5)	DP780	static	5.9	1678	Pull-out
DPM90S02 (A8)	DP780	static	5.9	1372	Interfacial
DPM00D01 (A10)	DP780	dynamic	5.9	9390	Interfacial
DPM00D02 (B1)	DP780	dynamic	5.9	12168	Interfacial
DPM00D03 (B2)	DP780	dynamic	5.9	10630	Interfacial
DPM30D01 (B3)	DP780	dynamic	5.9	11932	Interfacial
DPM30D02 (B4)	DP780	dynamic	5.9	15946	Interfacial
DPM30D03 (B6)	DP780	dynamic	5.9	16201	Interfacial
DPM90D01 (B8)	DP780	dynamic	5.9	7951	Pull-out
DPM90D02 (B9)	DP780	dynamic	5.9	5913	Pull-out
DPM90D03 (B10)	DP780	dynamic	5.9	5271	Pull-out

Typical load versus displacement curves for the mixed-mode specimens are shown in Figures 22 and 23.

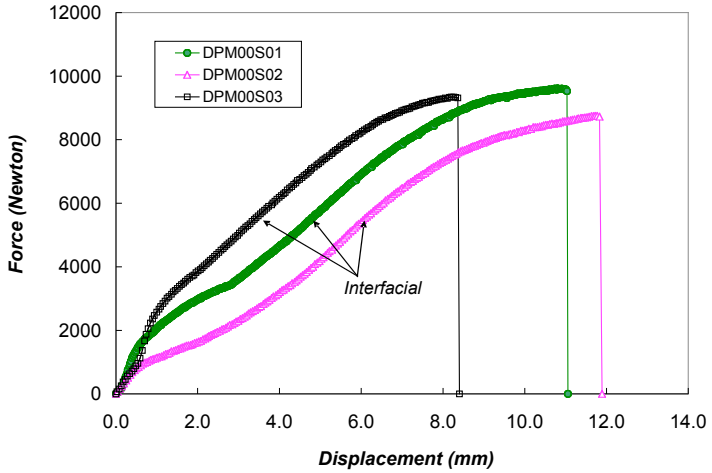


Fig. 22 Force versus displacement for mixed-mode specimen under static load (DP material, loading angle = 0^o)

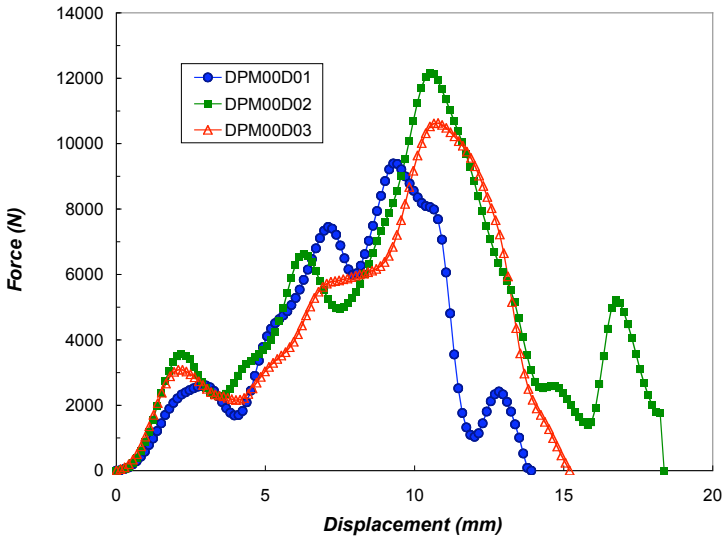


Fig. 23 Force versus displacement for mixed-mode specimen under dynamic load (DP material, loading angle = 0^o)

6. Conclusions

The common characteristics of the test data show that

(1) The peak load (or the strength) increases with weld nugget size.
(2) As the nugget diameter decreases the specimens are more prone to interfacial mode of failure.
(3) The peak load for LS specimen is higher than that for CT specimen under the same test conditions and weld configuration.

Comparing the two materials tested under the same other conditions,

(1) DP780 steel shows much higher peak load than mild steel.
(2) The increase of the peak load with impact speed is more in mild steel than in DP780.

It is observed that in mixed-mode tests when the loading angle is 90^o most specimens had the pull-out mode of failure while the interfacial failure mode prevailed in the other two loading angles (0^o, 30^o).

7. Appendix

Experimental data and the force versus displacement curves are provided in a separate CD attached with this report. This appendix lists the file names for the static tests, dynamic tests and mixed mode tests in Tables A-1, A-2 and A-3 respectively.

Table A-1: File names for static test data

Loading condition	Material	File name
Static	DP780	DP1CS DP1LS DP2CS DP2LS DP3CS DP3LS
	Mild steel	DQSK1CS DQSK1LS DQSK2CS DQSK2LS DQSK3CS DQSK3LS

Table A-2: File names for dynamic test data

Loading condition	Material	File name
Dynamic	DP780	DP1CDH DP1CDM DP1LDH DP1LDM DP2CDH DP2CDL DP2CDM DP2LDH DP2LDM DP3CDH DP3CDM DP3LDH DP3LDM
	Mild steel	DQSK1CDH DQSK1CDL DQSK1LDH DQSK1LDM DQSK2CDH DQSK2CDM DQSK2LDH DQSK2LDM DQSK3CDH DQSK3CDL DQSK3CDM DQSK3LDH DQSK3LDM

Table A-3: File names for the mixed-mode test data

Loading condition	Material	File name
Mixed-mode static	DP780	DPM00S DPM30S DPM90S
Mixed-mode dynamic	DP780	DPM00D DPM30D DPM90D

8. Data Computer Disk (CD)

   A CD containing test data and load versus displacement curves for all test specimens is attached here.

9. Acknowledgement

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materials and working with RoMan Engineering is greatly appreciated. Additionally, the professional support from Mr. Pat Villano of A/SP is also noted.

10. References

[1] ANSI/AWS/SAE/D8.9-97, *Recommended Practices for Test Methods for Evaluating the Resistance Spot Welding Behavior of Automotive Sheet Steel Materials*, American Welding Society, 1997.