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M. Peuler

R. Tremblay

Colin A. Rogers

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INELASTIC RESPONSE OF ARC-SPOT WELDED DECK-TO-FRAME CONNECTIONS FOR STEEL ROOF DECK DIAPHRAGMS

M. Peuler[1], C.A. Rogers[1] and R. Tremblay[2]

ABSTRACT

An experimental program was undertaken to investigate the inelastic seismic response of metal deck roof diaphragm systems. The load carrying capacity of roof diaphragms subjected to lateral loads is directly dependent on the shear strength of the connections. Hence, as part of this larger research program, a study on the inelastic performance of arc-spot welded deck-to-frame connections was completed. The connection project involved the monotonic, cyclic and seismic testing of 235 specimens, with and without weld washers, with different electrode types, and with various steel deck and frame thicknesses. Currently, welded washer connections are recommended for the improvement of weld quality and connectivity when thin deck material ($t \leq 0.71$ mm) is to be connected to the frame of the structure, not for the improvement of seismic performance. In general, the test results indicate that welded connections with washers exhibit higher ultimate capacities, as well as increased ductility and energy absorption ability in comparison with washerless connections. To achieve this performance, it is important to ensure that proper welding protocol is followed so that sufficient penetration into the frame material is obtained, especially for the thicker 1.21 and 1.52 mm sheet steels.

INTRODUCTION

In North America there are a sizable number of single-storey buildings, constructed for light industrial, commercial and recreational purposes, which are located in regions of active and moderate seismicity. Typically, a steel deck roof diaphragm is used in conjunction with vertical bracing to resist lateral loads caused by seismic activity. The diaphragm, composed of corrugated steel deck units fastened to one another and to the supporting steel frame, acts as a deep girder that depends on its connections to transfer lateral loads, *e.g.* wind and earthquake, to the wall bracing system. The individual deck units are connected to one another via sidelap fasteners, and to the roof frame by screws, nails, or welds. Arc-spot welds are the standard form of deck-to-frame connection found in Canada and in the United States. The sidelap connections carry inter-panel shear while the deck-to-frame connections transmit shear forces from the roof deck to the underlying structure and vice versa.

Capacity based design philosophy requires that one part of the lateral load resisting structure act as a sacrificial element to dissipate energy during seismic loading. The current methodology is to design the vertical wall braces to yield while the diaphragm and its connections are selected to

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[1] Dept. of Civ. Eng. and Appl. Mech. McGill University, Montreal QC, Canada.
[2] Dept. of Civ., Geo. and Mng. Eng., École Polytechnique, Montreal QC, Canada.

remain essentially elastic, *i.e.* a strong diaphragm *vs.* weak brace model. An alternative design approach is to allow the diaphragm, more specifically the deck area around the fasteners, to enter into the inelastic range in order to dissipate energy while the braces remain elastic. In this weak diaphragm *vs.* strong brace model it is crucial that the deck-to-frame connections exhibit stable ductile behaviour by maintaining their load carrying capacity during the inelastic deformation cycles, *i.e.* brittle shear failure or rapid post-peak capacity degradation does not occur.

The objective of this research was to determine if it is possible to rely on washers to improve the quality, the shear strength, as well as the energy absorption ability of welded connections when cyclically loaded in the inelastic range, and to recommend arc-spot welding techniques for use in seismic applications. Currently, it is recommended that washers be used when making arc-spot welded deck-to-frame connections involving thin sheet steel decking ($t \leq 0.71$ mm) to improve weld quality, not to increase diaphragm performance under seismic loads. No recommendations are made by the AISI Specification concerning the use of weld washers for sheet steels that are thicker than 0.71 mm *(AISI, 1999)*. Until recently, a minimal amount of data existed which could be used to describe the inelastic behaviour of arc-spot welded connections, *e.g.* Bond *et al. (2001)*. Additionally, current diaphragm design methods *(SDI, 1987; Davies and Bryan, 1982)* are based on data that consists of monotonic connection test results; hence, information on the cyclic and seismic performance of the various sidelap and frame fasteners was required.

This paper reports on the results of 235 laboratory shear tests performed on individual arc-spot welded deck-to-frame connections, with and without weld washers, with different washer and electrode types and sheet and frame thicknesses. Guidance for designers on the size and type of weld washer to use, along with information on appropriate welding protocols is given.

EXPERIMENTAL PROGRAM

Test Specimens and Set-Up

Test specimens were composed of various combinations of four different nominal sheet steel thicknesses (ASTM A653 *(1994)* 0.76, 0.91, 1.21 and 1.52 mm) which represent the roof deck, three plate thicknesses (1/8", 1/4" and 1/2") which act as the frame material, four different electrodes (E6010, E6011, E6022 and E7018) and three weld washers (bolt, wing, and modified), as shown in Fig. 1. Nominal properties of the connection components are presented in Table 1. Details on the welding protocols that were implemented are described in the following section.

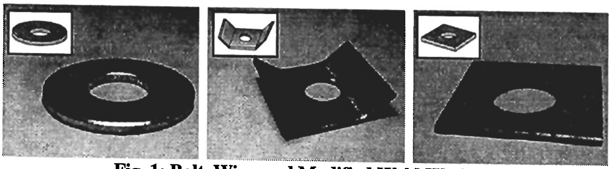


Fig. 1: Bolt, Wing and Modified Weld Washers

Each connection specimen was composed of a sheet steel and a plate component that were bolted to a test frame and actuator grip as shown in Fig. 2. The actuator was displaced according to the specified displacement protocols using an MTS control system, which imposed a shear load on the welded connection. The displacement of and loading on the connection were recorded using a data acquisition system.

Table 1: Specimen Component Properties

Sheet[1] Thickness (mm)	*Fy (MPa)*	*Fu (MPa)*	*Fu/Fy*	*% Elongation (50 mm ga)*
0.71	315	384	1.22	21.9
0.86	328	408	1.24	26.8
1.12	309	362	1.17	33.3
1.46	295	376	1.28	28.3

Washer Type	*Nominal Outer Dim. (mm)*	*Nominal Inner Dia. (mm)*	*Nominal Washer Thickness (mm)*
Bolt-type	35	14	2.5
Wing-type	28 × 25.5	10	1.5
Modified	32 × 32	14	1.5

Electrode Type	*Nominal Diameter (mm)*	*Nominal Xu (MPa)*
E6010	3.2	414
E6011	3.2	414
E6022	3.2	414
E7018	3.2	483

Plate Thickness (in (mm))	*Nominal Fy (MPa)*	*Nominal Fu (MPa)*
1/8 (3.18)	300	450
1/4 (6.35)	300	450
1/2 (12.7)	300	450

[1] Measured base metal thickness values for 0.76, 0.91, 1.21 and 1.52 mm nominal thickness deck.

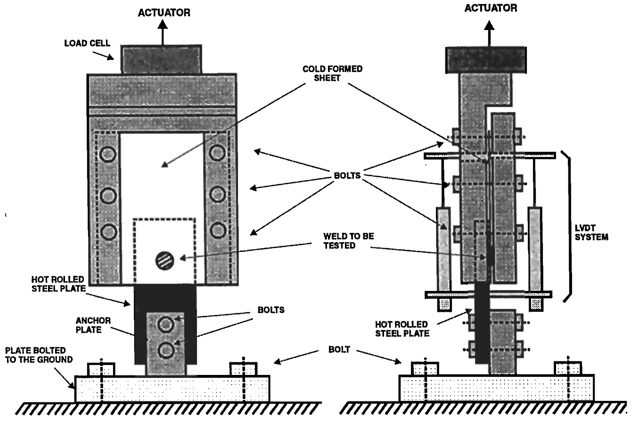


Fig. 2: Test Set-Up

Displacement Protocols

Monotonic, cyclic and simulated earthquake loads were imposed on the connection specimens. The monotonic tension tests were carried out up to 15 mm displacement at a rate of 0.5 mm/minute. The cyclic tests were completed at 0.2 Hz under stroke control with a displacement range from ±0.5 mm

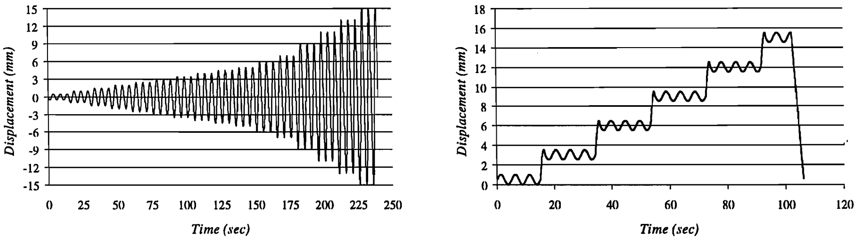


Fig. 3: Displacement Protocols

to ±15 mm with 16 increments of 3 cycles at the same amplitude (Fig. 3). The simulated seismic tests were also stroke controlled, and consisted of a series of low amplitude 0.2 Hz cycles (±0.5 mm), followed by a single jump of 2.5 mm. The displacement protocols reflect the anticipated maximum ductility demand on a single frame connector in a roof diaphragm under seismic loading *(Rogers and Tremblay, 2000; Essa et al., 2001).*

Welding Protocols

Due to the many variables involved in the arc-spot weld fabrication process for deck-to-frame connections, it was essential to maintain consistent weld quality through the entire test program. Therefore, the welding was carried out in the laboratory by a certified welder according to the recommendations of and under the supervision of a welding engineering company, Sodovec Inc. of Laval, Quebec. For welds with and without washers, the recommendations include:

a) The visible weld diameter must be from 5/8" (16 mm) to 3/4" (19 mm).
b) At least 75% of the weld circumference must be fused to the surrounding sheet.
c) The weld profile must be convex, approximately 1/32" (1.2 mm) in height.
d) The molten metal should not pass through the supporting steel structure.
e) The slag should be removed after the weld is deposited.
f) The welds must be uniform and free of cracks, inclusions, spillovers and excessive rutting.

Welding Procedure

The welding procedures were as follows:

a) For welds with *no washer*, the arc was sparked at the centre of the weld location, and then spiralled outward until the desired diameter was reached. At this point, the arc was brought back to the centre of the weld and was withdrawn vertically.
b) For welds *with washers*, the arc was sparked on the inside edge of the washer hole and the weld was made in a circular motion along the inside edge until the starting point was reached. At this point the electrode was spiralled inward until the weld centre was reached and the arc was withdrawn vertically.

In all cases the arc-spot welds were required to penetrate through the sheet steel and into the plate material. Hence, it was necessary to combine the above welding technique with a "pushing down" of the electrode tip into the molten metal in order to "feel" the tip piercing through the sheet steel, and into the underlying steel plate. This procedure was especially important when thick gauge sheet steel specimens were being connected, *i.e.* 1.21 and 1.52 mm, in combination with the 1/4" and 1/2" underlying plates. The additional vertical movement of the electrode was necessary because the washers, thick sheets, and thick plates all acted as heat sinks, causing the heat of welding to spread horizontally rather than being focused at the connector location.

The amperage was adjusted according to the electrode, the steel thickness and the use of a weld washer. The time needed to complete the various welded connections varied between 5 and 22 seconds, depending on the steel thickness, washer type, and the electrode type. The majority of connections (141) were welded using the E6010 electrode, as compared to 37 for the E6011, 33 for the E6022, and 24 for the E7018.

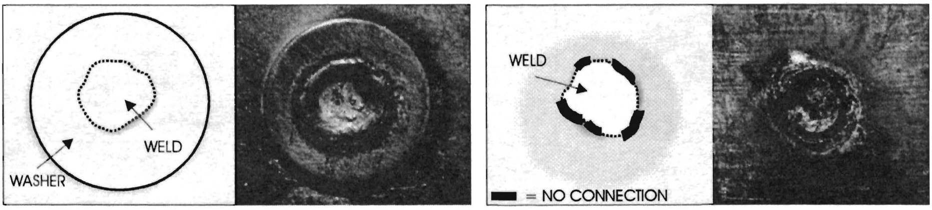
WELD QUALITY

Workmanship

Arc-spot welding of deck-to-frame connections is a complex operation; hence, competence on the part of the welder is necessary to obtain welds of an acceptable quality. The high amperage required to form an arc-spot weld generates extensive heat, which can literally burn away the sheet steel material that surrounds the weld, resulting in a less-than-complete perimeter connection. The use of washers aids in reducing this sheet burning effect. The fabrication of connections with bolt washers, which are thicker than the other washers and have a larger hole diameter than the wing washers (Table 1), required additional time due to the need to fill the hole with weld material. In some cases this resulted in overheating of the welding area, causing the washer to begin to burn away, and ultimately forcing the welder to stop. At this point, the incomplete weld would often have a depression in its middle. The welder was then forced to start welding once again on the same weld, in order to add additional weld material to fill the hole and to obtain the required bulge. The finished weld was visually indistinguishable from one that was properly welded. The welder found that better quality welds could be made with the wing washers because of the smaller diameter hole and the reduced thickness. The burn-through effect was not as pronounced for the E7018 filler electrode because it required lower burning times, which resulted in a better visual weld quality than the penetration electrodes (E6010, E6011, and E6022).

Percent Connectivity

The *percent connectivity* of an arc-spot weld refers to the percent of the weld perimeter that is fused to the surrounding sheet (Fig. 4). This measure of weld quality is a subjective visual estimate, and therefore contains some margin of error. Nonetheless, it does provide an indication of how well the weld has been formed.



100 % Connectivity

Approx. 50% Connectivity

Fig. 4: Arc-Spot Weld Percent Connectivity

The percent connectivity increased with the sheet steel thickness when no weld washer was used. As shown in Fig. 5, for the thickest sheet (1.52 mm) all of the no-washer specimens had 100% connectivity. The thinner sheet steels were more susceptible to burning during the welding process as indicated by the increase in variability and decrease in connectivity of the weld perimeter for the 0.76 and 0.91 mm connection specimens. However, when a weld washer was used, all connections had 100% connectivity at the visible surface of the washer regardless of sheet thickness, which suggests that a complete connection between the sheet and weld metal was achieved.

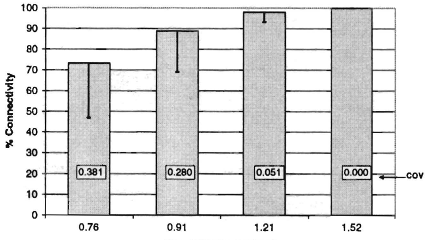


Fig. 5: Percent Connectivity for No-Washer Connections

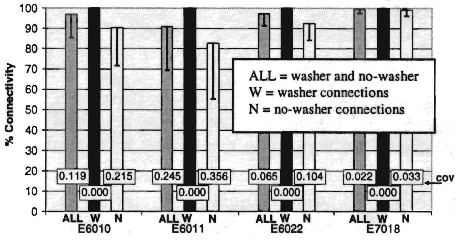


Fig. 6: Percent Connectivity Comparison by Electrode Type

The E6010, E6011 and E6022 electrodes are designed to have good penetration qualities, whereas the E7018 is only mildly-penetrating with some "filler" qualities. Test results for the no-washer connections indicate that the E7018 electrode produces an arc-spot weld with high percent connectivity and lower scatter (Fig. 6).

Visible Weld Diameter

The visible weld diameter, d_{vis}, is the diameter of the fusion zone after the slag has been removed, measured across the centre of the weld in plan view (Fig. 7). For irregularly shaped welds, the minimum diameter across the weld was measured. Table 2 lists the statistical parameters of visible weld diameters resulting from the use of the different washer types. In general, using a bolt or modified washer produced the greatest diameter welds, mainly due to the larger hole diameter.

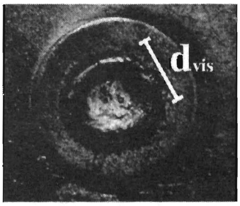


Fig. 7: Visible Weld Diameter

Table 2: Visible Weld Diameter

Washer Type	*Avg. dvis (mm)*	*Std. Dev. (mm)*	*COV*
Bolt-type	17.0	1.87	0.11
Wing-type	15.2	1.80	0.12
Modified	17.0	1.50	0.10
None	16.3	2.29	0.14

Effective Weld Diameter

The amount of penetration into the plate can be measured by the *effective weld diameter*, d_{eff}, *i.e.* the diameter of the intersection between the fusion zone and the steel plate (Fig. 8). It is normally assumed that the effective weld diameter, rather than the visible weld diameter, is directly related to the shear strength of an arc-spot weld. Peköz and McGuire *(1979)* developed the following equation for d_{eff} based on the results of tests carried out on arc-spot weld specimens without weld washers:

$$d_{eff} = 0.7d_{vis} - 1.5t \tag{1}$$

where the sheet thickness, t, d_{eff} and d_{vis} are in millimetres. Once testing had been completed the weld nugget was milled flush to the surface of the underlying plate and the effective weld diameter for each connection specimen was measured. These measured d_{eff} values were then normalized using Eq. 1 to remove the effect of the variable visible weld size. As shown in Figs. 9 and 10, Eq. 1 generally provides a conservative estimate of the effective weld diameter.

Typically, the deeper the weld penetrates into the plate, the larger the effective diameter. In general, those connections without washers had a greater effective weld diameter because there was less material to act as a heat sink (Fig. 9). In contrast, the washer acts as a dam to stop the molten material from spreading, and the welder can rely on the washer hole as a guide. In the washer connections, those fabricated with the modified washer provided the largest effective weld diameter due to the thinner material used and the larger hole (Table 1). The wing washer seemed to result in a lower penetration, (lower values for 0.76-1.21 mm and larger scatter for 1.52 mm), most likely due to its smaller hole diameter. The test results show that when proper weld protocols are used, no discernable change regarding the effective weld diameter is evident with respect to the thickness of the sheet steel (Fig. 10). Based on the normalized d_{eff} values it can also be observed that the E7018 electrode provided slightly less penetration than the remaining electrodes. Among the E60 electrodes the E6011 exhibited the largest normalized effective weld diameter. Note that the results for the 0.76 mm E7018 (Fig. 10) are composed only of washer connections.

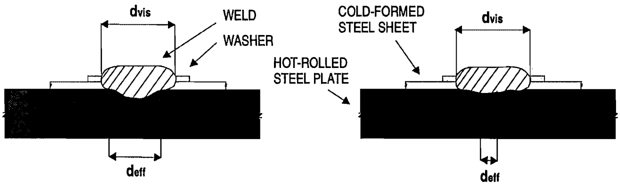


Fig. 8: Cross-Section Showing Effective Weld Diameter

Fig. 9: Effective Weld Diameter as a Function of Sheet Thickness and Washer Type (N = no washer, B = bolt washer, W = wing washer, M = modified washer)

Fig. 10: Effective Weld Diameter as a Function of Sheet Thickness and Electrode Type

Weld Quality Conclusions

It is difficult to obtain full perimeter connectivity without the use of a washer when welding 0.76 and 0.91 mm sheet steels. An E7018 electrode provides the highest percent connectivity for these types of connections. In general, the use of any washer type will improve the visible connection between the sheet steel and the weld perimeter from that obtained when no washer is specified. However, the use of a washer may reduce the amount of weld penetration (effective weld diameter) into the underlying plate, where the smaller the washer hole diameter, the less penetration that is achieved. The most effective washer type is fabricated from a thin material with a large diameter hole. The welder did comment that the wing washer was the easiest to weld, although it essentially possessed too small of a hole diameter to obtain sufficient penetration as indicated by the test results. Furthermore, the proximity of the hole to the bends of the wing may affect the formation of the weld due to the possibility of burning through the bends of the washer. The degree of penetration of the weld into the plate can also be affected by the electrode; where of the E60 types the E6011 connection specimens had the largest normalized effective diameters. On the other hand, the E7018 electrode, which displayed good percent connectivity ability, was not able to penetrate into the plate to the same extent as the E60 electrodes.

TEST RESULTS

Failure Modes

The basic failure modes observed during shear testing of the connection specimens include:

Shear failure of the fusion zone through the shear plane along the top surface of the steel plate where the weld remains attached to the sheet steel. It results in a brittle fracture of the entire connection with no residual capacity. This can occur in both washer and no-washer connections, but is usually seen in washer connections that do not have adequate penetration. In this test program the shear type of failure occurred very rarely; *i.e.* in 9 washer test specimens, 7 of which were made with the wing washer (both 1.21 and 1.52 mm sheets) and 2 with the bolt washer (1.52 mm sheet), or approximately 4% of the connections. It is important to note that for every specimen that failed suddenly by shear, the percent connectivity was 100% and the weld appeared to be very sound by visual inspection. However, the measured effective diameter, d_{eff}, for the 7 wing washer connections ranged between 6.5 and 9.5 mm with a mean of 7.3 mm, and the ratio of measured to calculated d_{eff} was 0.82. Likewise, the mean measured effective diameter, d_{eff}, for the 2 bolt washer connections was 9.4 mm, and the ratio of measured to calculated d_{eff} was 0.92. Hence, the shear failure that was observed for these connections can be attributed to a lack of penetration into the frame material.

Bond failure on the tension side of the sheet-to-weld metal connection with some sheet buckling on the compression side. Different behaviour was observed for washer and no-washer connections:

In **no-washer** connections the weld perimeter separates from the surrounding sheet steel and the weld nugget is left in the plate. This represents a sudden fracture of the bond between the tension side of the weld and the adjacent sheet steel, *not* between the weld and the underlying plate and does not cause a brittle fracture of the connection as a whole. Usually the sheet steel bears against the compression side of the weld nugget, forming buckles locally in the sheet around the weld, characteristic of a bearing failure. With increased displacement or under reversed cyclic loads complete separation of the sheet and the plate is common.

In **washer** connections the perimeter separates in a similar fashion, although afterwards the washer holds the sheet in place and some load can continue to be carried by the sheet bearing on the weld nugget and the washer edge. This results in extensive buckling of the sheet steel on the compression side of the connection and the formation of an extended oval hole in the sheet steel. The weld metal and washer are left attached to the plate. This type of failure may also cause tearing of the sheet steel on the compression side of the washer if displacements are large enough.

In terms of seismic performance it is essential that bond failure take place rather than shear failure of the weld nugget. This permits energy to be dissipated through the inelastic localized buckling deformation of the sheet material around the weld in the post-ultimate load range. To develop this behaviour it is necessary to have adequate penetration of the weld into the underlying frame. In addition, there must also exist a means to ensure that the sheet steel will bear on the weld nugget once bond failure has taken place. Qualitatively, the bolt washer best performs this function because of its relatively large outer diameter and stiffness.

Effect of the Use of Washers on the Ultimate Shear Strength

The effect on the connection shear strength, P_u, of adding a washer according to sheet thickness is illustrated in Fig. 11, for the E6010 electrode. The shear strength values have been normalized with respect to the visible weld diameter. Overall, a washer improves the capacity and consistency of the thinner sheet steel connections, whereas for the 1.52 mm sheets, when all test specimen results are considered, the opposite result was observed together with greater scatter. Note that a similar trend was found for the other electrodes and for all displacement protocols. However, if only the connections that failed by bond are considered, *i.e.* the 9 shear failure specimens are not included, then the mean normalized P_u value for the washer connections increases, and the coefficient of variation decreases for both the 1.21 and 1.52 mm sheets. In this case all of the sheet thicknesses exhibit an increase in shear capacity when washers are utilized. The mean normalized P_u values for the 1.21 and 1.52 mm sheet connections are 1.56 and 1.93 kN/mm, respectively.

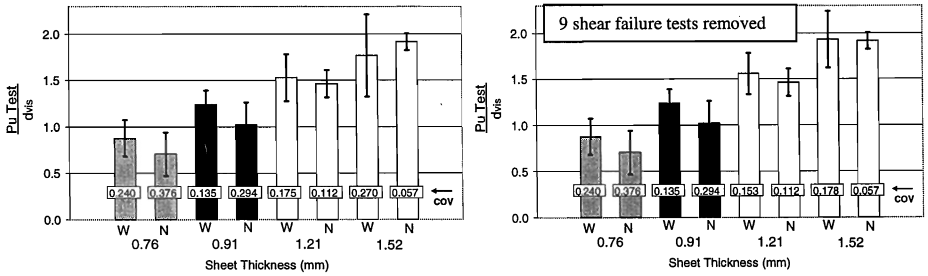


Fig. 11: Normalized Ultimate Shear Strength of E6010 Electrode Connections Categorized According to Sheet Thickness and the Use of a Weld Washer (W=washer, N=no washer)

Effect of Washer Type Under Monotonic Loading

The relative performance of the connections with different washer types (Fig. 1) was evaluated with regards to shear strength when subjected to monotonic loading. The specimens on which this section is based were fabricated using a 0.91 mm sheet, a 1/4" (6.35 mm) plate and an E6010 electrode. A difference only exists in the type of washer used (bolt, wing or modified). This group of specimens was selected for comparison because typically, the thin sheet steels show a greater improvement in performance when a washer is used in comparison to the thick sheet connections. Similar results were found using the 0.76 mm sheet steel connections.

Figure 12 illustrates the typical failure configurations for connections under monotonic loading, as well as the corresponding load versus displacement graphs. Overall, the observed behaviour is consistent for all connection types; the ultimate load, due to bond failure, was reached at a similar displacement (Table 3) followed by a subsequent bearing response. As shown in Table 3, the no-washer connections produced the lowest ultimate loads due to the lower percent connectivity for thin sheets (Fig. 5). In the post-ultimate range the washer connections were better able to carry load because of their more efficient bearing mechanism.

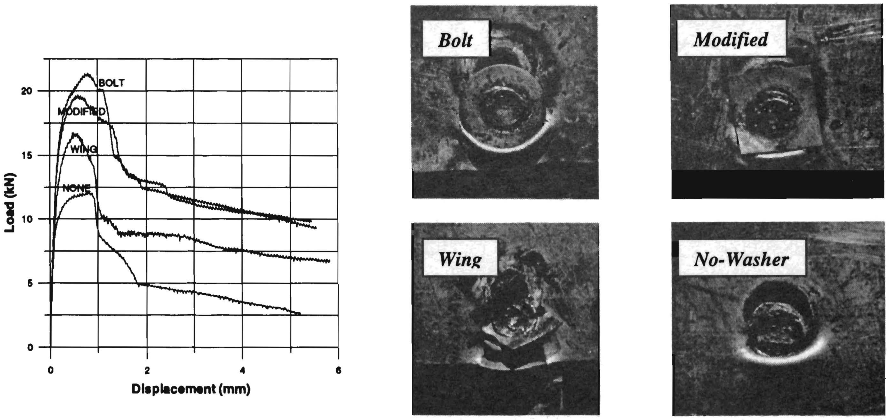


Fig. 12: Bolt, Wing, Modified and No-Washer Specimens Under Monotonic Loading

Table 3: Washer Comparison for Monotonic Loading

Washer Type	*Loading Protocol*			*Standard Deviation*	*COV*
BOLT	**Monotonic**	**Avg. Ultimate Load (kN)**	20.8	1.09	0.12
		Avg. (Ultimate Load/dvis)	1.29	0.20	0.37
		Avg. Displacement at Max Load (mm)	0.79	0.05	0.14
WING	**Monotonic**	**Avg. Ultimate Load (kN)**	16.6	0.51	0.07
		Avg. (Ultimate Load/dvis)	1.06	0.07	0.15
		Avg. Displacement at Max Load (mm)	0.67	0.18	0.64
MODIFIED	**Monotonic**	**Avg. Ultimate Load (kN)**	20.7	1.56	0.18
		Avg. (Ultimate Load/dvis)	1.34	0.21	0.37
		Avg. Displacement at Max Load (mm)	0.79	0.27	0.82
NONE	**Monotonic**	**Avg. Ultimate Load (kN)**	13.2	3.10	0.56
		Avg. (Ultimate Load/dvis)	0.87	0.15	0.26
		Avg. Displacement at Max Load (mm)	0.59	0.27	1.09

Effect of Washer Under Cyclic Loading

The cyclically loaded washer connections performed in a similar fashion to those tested with the monotonic protocol. In contrast, the no-washer connection performance differed because both sides of the weld nugget and the surrounding sheet steel were loaded in tension at some point during the displacement protocol. Hence, the connection between the sheet steel and the weld was broken, and only a minimal residual capacity existed. This behaviour is illustrated in the load *vs.* deformation hystereses provided in Fig. 13, where the no-washer connection has near zero shear capacity after

Table 4: Washer Comparison for Cyclic Loading

Washer Type	*Loading Protocol*			*Standard Deviation*	*COV*
BOLT	**Cyclic**	**Avg. Ultimate Load (kN)**	19.8	0.37	0.04
		Avg. (Ultimate Load/dvis)	1.22	0.03	0.05
		Avg. Displacement at Max Load (mm)	0.58	0.06	0.25
		Avg. Max Energy (kN-mm)	698	70.6	0.24
WING	**Cyclic**	**Avg. Ultimate Load (kN)**	15.5	1.35	0.21
		Avg. (Ultimate Load/dvis)	1.15	0.21	0.43
		Avg. Displacement at Max Load (mm)	0.51	0.10	0.46
		Avg. Max Energy (kN-mm)	649	101	0.37
MODIFIED	**Cyclic**	**Avg. Ultimate Load (kN)**	22.6	0.83	0.09
		Avg. (Ultimate Load/dvis)	1.38	0.01	0.01
		Avg. Displacement at Max Load (mm)	0.49	0.03	0.16
		Avg. Max Energy (kN-mm)	630	33.3	0.13
NONE	**Cyclic**	**Avg. Ultimate Load (kN)**	19.1	0.83	0.10
		Avg. (Ultimate Load/dvis)	1.27	0.09	0.17
		Avg. Displacement at Max Load (mm)	0.40	0.03	0.15
		Avg. Max Energy (kN-mm)	246	39.1	0.38

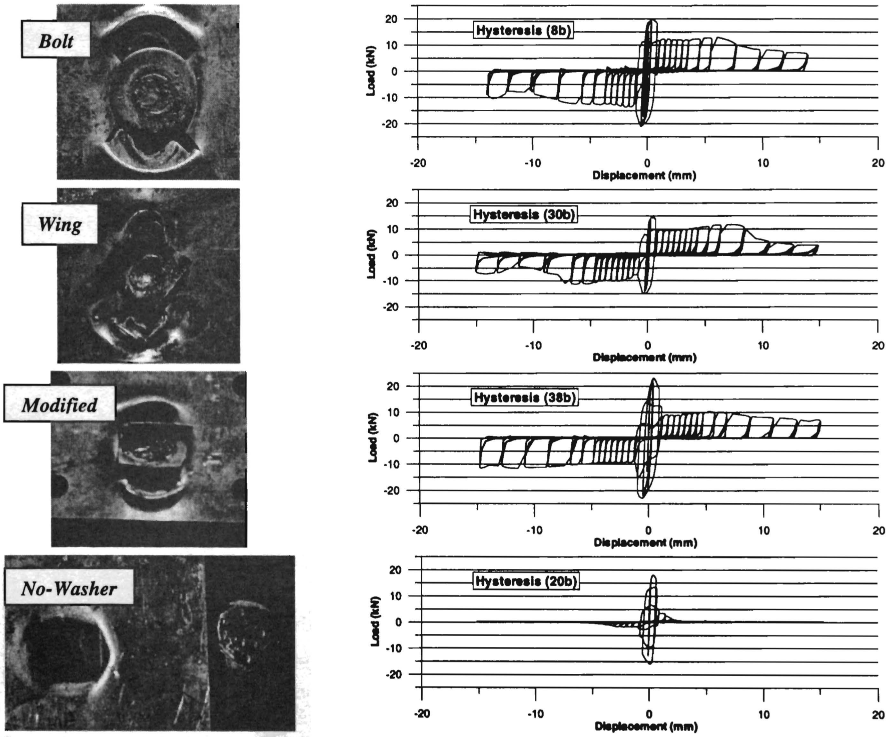


Fig. 13: Bolt, Wing, Modified and No-Washer Specimens Under Cyclic Loading.

only a few cycles (typically within less than 2 mm), whereas the washer connections were able to carry load at large displacements. The ultimate load for the washer and no-washer connections is reached at the same displacement when bond failure between the sheet steel and the weld takes place. In the washer connections a residual bearing capacity is then realised because the sheet steel is held between the plate and washer. Normally, tearing of the sheet steel and a subsequent decrease in the bearing capacity occurs in the range of ±7 mm. It also must be noted that the cyclic behaviour is pinched with near zero shear capacity.

For each specimen, the dissipated energy was determined based on the area enclosed within the load-displacement hysteresis curve, with the average values presented in Table 4. The different washer connections dissipated a similar amount of energy, because this characteristic is controlled mainly by the bearing capacity of the connection, which was consistent regardless of the washer type. However, the washer connections dissipated significantly more energy over the entire cyclic displacement protocol (630–698 kN-mm), than the no-washer connections (246 kN-mm). To dissipate energy under cyclic or seismic loading it is essential that shear failure of the weld nugget not take place; hence adequate penetration of the weld into the plate must exist.

Ultimate Shear Strength

The ultimate load reached during the testing of each specimen, P_{uT}, was compared to the ultimate nominal shear strength, P_{uP}, predicted by equations given in the following design standards: AISI *(1999)*, SDI *(1987)*, Eurocode *(1996)*, CSSBI *(1991)* / S136 *(1994)*, and the Stressed Skin Diaphragm Design approach *(Davies and Bryan, 1982)*. A listing of the design equations can be found in Peuler *(2002)*. The overall accuracy of the different codes, regardless of the type of loading is shown graphically in Fig. 14 for the no-washer connections. In general, the statistical results demonstrate that the predictions of ultimate shear capacity of arc-spot welds using the AISI, CSSBI/S136, and SDI design standards are conservative ($P_{uT}/P_{uP} \geq 1$), whereas, the Eurocode and Stressed Skin approaches are significantly more conservative ($P_{uT}/P_{uP} = 2.775 \pm 0.55$ and 2.624 ± 0.53, respectively). The SDI method produces the least conservative estimate ($P_{uT}/P_{uP} = 1.19 \pm 0.39$).

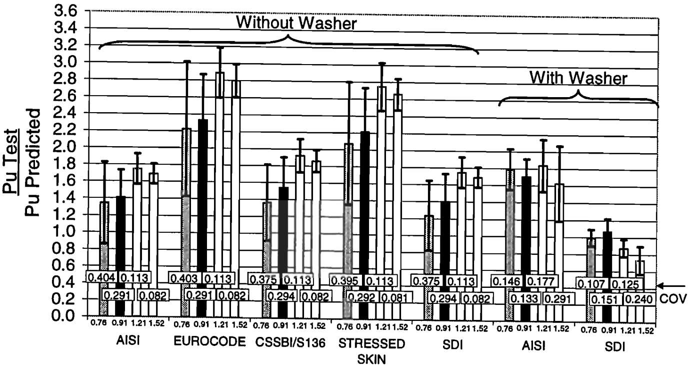


Fig. 14: Ultimate Strength Test-to-Predicted Design Standard Comparisons

For all methods the test-to-predicted ratio increased for sheet thicknesses up to 1.21 mm, after which a slight decrease occurred. The variability in test results is reduced for the 1.21 and 1.52 mm sheet steel specimens, due to the improved percent connectivity for these connections.

The same comparison for the washer connections can also be seen in Fig. 14. Given that all of the methods except for the SDI do not account for the presence of washers, only the values for the AISI method are shown to illustrate the general trend in behaviour of the washer connections. Except for the SDI predictions, the design methods could be used to consistently predict the shear capacity regardless of sheet thickness, although the shear capacity predictions are generally conservative. The test-to-predicted values for the four sheet thicknesses (with washers) become more consistent when the 9 shear failure specimens are excluded, *i.e.* the mean test-to-predicted AISI values of 1.79, 1.71, 1.87 and 1.77 for the 0.76 through 1.52 mm sheets are now obtained. The consistent results can be attributed to the improved percent connectivity of the welds when washers are provided. In contrast, the SDI is the only standard that specifies a separate equation for no-washer and washer connections. The results of this test program reveal that the washer equation provides an unconservative estimate of the shear capacity with a large scatter, which becomes more evident as the sheet thickness increases. However, it must be noted that this SDI equation was intended to be used for the design of 0.71 mm and thinner steel sheets. Even when the washer connections that failed by shear are removed from the data set the unconservative trend remains.

Energy Dissipation

The normalized energy values, E/P_u, measured up to the end of the 2 mm and 5 mm cycles were categorized by electrode type and the use of weld washers (Fig. 15). A comparison of the effect of the sheet thickness on the same energy parameters specifically using the E6010 electrode test specimens is presented in Fig. 16. The 5 mm displacement range represents the limit beyond which the connection would typically not be used because of the onset of sheet tearing. The 2 mm displacement range was selected because at this point almost all connections were able to carry some load. Overall, it is clear that the connections with washers are able to dissipate more energy in comparison with the no-washer connections regardless of electrode type. However, at the 2 mm deformation level the typical no-washer connection is still able to carry some shear load and hence the difference in energy dissipation ability is not extensive. No definite trend with respect to electrode type can be seen from the results, which indicates that any of the electrodes may be used as long as the weld quality is ensured through proper weld protocols. The variation in energy dissipation capability between the types of electrodes may be skewed by the pronounced difference in sample sizes between the electrodes, and because shear failure of the weld nugget occurred for 9 of the thicker E6010 test specimens *(Peuler, 2002)*. If these 9 tests are not included in the 2 mm cycle results, then the E6010 mean value for washer connections improves from 7.46 to 8.30 kN-mm/kN, and the coefficient of variation decreases from 0.363 to 0.238. An improvement was also observed for the 5 mm cycle results when the shear failure specimens were not included, *i.e.* the mean E/P_u value increased from 16.1 to 18.0 kN-mm/kN, and the coefficient of variation dropped from 0.418 to 0.264 for the E6010 washer connections. Similar energy dissipation results were obtained for the seismic tests.

In Fig. 16 it can be observed that the use of a washer is beneficial for the 0.76 and 0.91 mm sheet specimens due to the improved percent connectivity. For the thicker sheet connections at short displacements the no-washer connections, with their increased percent connectivity, were able to carry load and thus increase the total energy that was dissipated. At the 5 mm displacement level the use of a washer was effective in dissipating energy for those connections that did not fail by shear of the weld, *i.e.* the two 1.52 mm bolt washer connections, five 1.52 mm wing washer specimens, and two 1.21 mm wing washer specimens were not considered. The large scatter recorded for the thicker sheet steels shows the effect on the energy dissipation of the specimens that failed in a brittle shear mode. The 2 mm cycle washer connection statistical results determined without the specimens that failed by shear are significantly better, with a mean E/P_u value of 8.72 and 8.82 kN-mm/kN for the 1.21 and 1.52 mm tests, respectively, as well as an improved coefficient of variation of 0.182 and 0.067. This compares with the 0.423 and 0.687 COV values shown in Fig. 16. Likewise, at the end of the 5 mm cycles the mean normalized energy values increase and the scatter of results decrease when the shear failure specimens are neglected. For the 1.21 mm washer specimens the mean E/P_u value improves from 18.9 to 20.7 kN-mm/kN, while the coefficient of variation drops from 0.467 to 0.300. Similarly, the mean E/P_u value for the 1.52 mm washer specimens changes from 11.5 to 18.8 kN-mm/kN and the scatter diminishes, as shown by the COV decrease from 0.988 to 0.319.

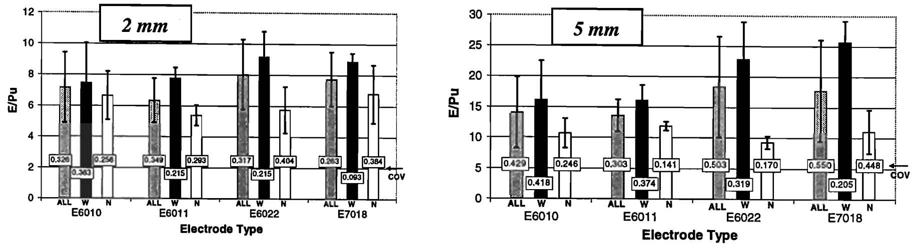


Fig. 15: Cyclic Energy Dissipation up to End of 2 mm and 5 mm Displacement Cycles

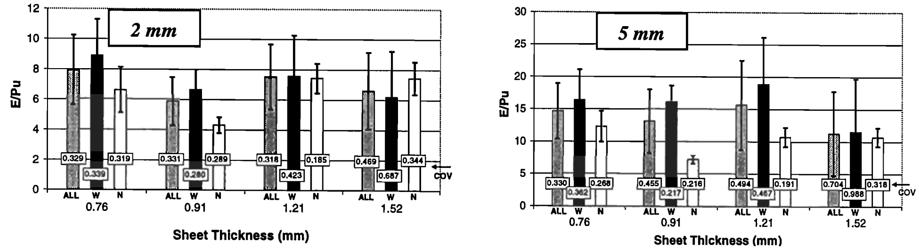


Fig. 16: Cyclic Energy Dissipation up to End of 2 mm and 5 mm Cycles, for E6010 Electrode Specimens

CONCLUSIONS

The results of 235 individual arc-spot weld roof deck-to-frame connection tests have been compiled in order to evaluate their inelastic response with and without washers. Various sheet steel thickness, washer and electrode types, as well as displacement protocols were included in the study. In terms of workmanship and quality, the arc-spot welding process can be considered as difficult; however a qualified welder following proper welding procedures can produce connections that have both good perimeter connectivity and penetration. The use of no-washer welds caused the percent connectivity to be less than 100% for the 0.76 and 0.91 mm sheet specimens, especially when the E60 electrodes were used. An improvement in quality was realised with the specification of washers, where the wing washer best facilitated welding. The current effective weld diameter equation was shown to be adequate for the different sheet and washer types that were tested.

Different failure modes may take place when an arc-spot weld is loaded in shear. In seismic design where the roof deck diaphragm is expected to act as the energy-absorbing fuse in the lateral load resisting system, it is necessary that the connections fail in a non-brittle manner, *i.e.* by bond separation at the weld-to-sheet interface followed by bearing distortion of the surrounding sheet steel. Shear failure of the weld nugget must be avoided because the connection exhibits no ductility. In the test program, only 9 specimens (4%) exhibited shear failure due to a lack of penetration. Out of these shear failure specimens 7 were constructed with a wing washer and all were composed of 1.21 or 1.52 mm thick sheets. When considering the bond failure of no-washer and washer connections the ultimate shear resistance is reached at a similar level due to the shared failure mechanism (bond separation). The washer connections are then able to carry post-ultimate loads over large displacements through bearing behaviour, whereas the no-washer connections typically lose most of their capacity typically within less than 2 mm displacement. It is common in the washer connections for tearing of the sheet to occur at approximately ±7 mm displacement which causes a decrease in the bearing capacity. It is also important to note for seismic purposes that the load *vs.* displacement hysteresis of the connections is severely pinched.

The ultimate shear strength of the 0.76 and 0.91 mm sheet connections under monotonic and cyclic loading improves when weld washers are used because of the increased percent connectivity. In the cases where a thicker deck material is specified, the use of a washer provides a slight increase in the shear capacity. It is especially important to note that the use of a washer with a relatively small diameter hole, *i.e.* as found for the wing washers, with a thick sheet steel may lead to inadequate penetration and the possibility of brittle shear failure in the weld nugget, as occurred for nine of the tests that were completed. In general, the existing design equations from North American and European standards for the shear capacity of a weld are conservative. An exception exists for the weld washer equation that is specified by the Steel Deck Institute Diaphragm Design Manual, which resulted in unconservative strength predictions when used for the design of materials between 0.76 and 1.52 mm thick.

A strong brace *vs.* weak diaphragm seismic design approach requires that the diaphragm connections are able to dissipate energy through inelastic deformations. It has been shown that washers improve the performance of deck-to-frame connections when considering this characteristic by ensuring that bearing distortion takes place after the ultimate load is reached. The shear deformation of the fastener should, however, be kept below 5 mm to limit tearing of the sheet steel. At this deformation level a single fastener was found to exhibit a pinched hysteretic behaviour. It is expected that this behaviour will be less pronounced in a full-scale diaphragm due to the inherent redundancy of the roof assembly that allows for the redistribution of the inelastic demand to a large number of fasteners.

As a general conclusion, it is recommended that for seismic design weld washers be used to make certain that the roof diaphragm will be able to sustain inelastic deformations while maintaining a load capacity. A variety of weld washers and electrode types may be specified for use with the 0.76 and 0.91 mm roof decks as long as proper welding protocols are followed to ensure adequate quality in terms of percent connectivity and penetration. The use of weld washers with the thicker deck panels may also be advantageous with respect to energy absorption ability if shear failure due to a lack of penetration is prevented through the specification of proper welding protocols. At this stage it is recommended that an adapted wing washer with a larger hole (14 mm) and a larger edge distance to the bends should be utilised to reduce the possibility of inadequate penetration into the frame material.

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