WELDING NEWLY DEVEL0PED, HIGH STRENGTH, SEISMIC GRADE REINFORCING BARS

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SUMMARY

The paper describes research undertaken to qualify welding procedures for two grades of newly developed seismic reinforcing bars. The 300E grade with a minimum yield strength of 300MPa and a minimum uniform elongation of 15% and the 500E grade with a minimum yield strength of 500MPa and an uniform elongation of 10% were developed to meet the new joint Australian/New Zealand Steel Reinforcing Material. Welding these earthquake safe reinforcing bar grades to the currently reviewed AS/NZS 1554.3 Reinforcement Bar Welding Standard not only requires matching the strength of the bars, but also meeting an associated minimum tensile to yield ratio of 1.15. New, more economic as well as practically desirable joint alternatives, previously not covered in AS 1554.3, have also been tested with the aim to introduce them in the new issue of AS/NZS 1554.3. A strain age embrittlement test to check the weldability in cold formed areas has also been performed.

INTRODUCTION

Seismic Requirements

Seismic demands on a reinforced concrete structure under a massive earthquake are enormous. Modern limit sate design principles allow deliberately for controlled damage of the structure to occur. This design principle allows for economic building and no to very low damage for the standard earthquake and controlled but not catastrophic damage in the case of a very severe earthquake.

In order to achieve the required plastic deformation under high earthquake loads, for seismic grade reinforcement bars limits are set not only for the yield strength, but also for the tensile (R_m) to yield (R_e) ratio in both directions. The minimum value of the ratio R_m/R_e is to ensure that yielding will not be confined to where it first commences, thereby permitting greater elongation of the bar before fracture and hence greater ductility of the structural member. The maximum value is to ensure that when the steel commences to strain harden the stress in the bar does not lead to a significant over strength of the structural member. This is important for the applied capacity design procedure to work, which is intended to ensure an appropriate balance of capacity of members and failure modes securing satisfactory post elastic (plastic) behaviour in a major earthquake.

The guiding principle for the welded connection is that the weld should have sufficient tensile strength for not to be the weakest link. However the weld should also contribute to the deformation requirements and therefore the weld should provide yielding close to the yield of the parent bar combined with acceptable elongation. As a result the minimum value for the tensile to yield ration R_m/R_e has been set as also being valid for the welded region. However, following the rule that the tensile capacity of the welded region should exceed the tensile capacity of the bar, there is no maximum limit for R_m/R_e set for the welded joint.

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Mechanical Properties of Reinforcement Steels

In the new revision of the Australian/New Zealand Steel Reinforcing Materials Standard [1], which will be a revision and amalgamation of AS 1302-1991, AS 1303-1991, AS1304-1991, NZS 3402:1989, NZS3422:1975, and NZS3421:1975, the mechanical properties of reinforcement steels are most likely to be as shown in table 1.

Table 1: Mechanical Properties of Reinforcing Steels
(from Table 2 of Draft 980203 Doc Id: 6875.BD/84-0030/452; Standards Australia)

Property	**500L**	**500N**	**250N** 1)	**500E (Seismic)**	**300E (Seismic)**	**Type of Specified Value**
Nominal diameter 2) (mm)	4 3) to 16	6 to 40	6 to 36	6 to 40	6 to 40	
Characteristic yield Stress (MPa) $R_{ek.L}$	500	500		500	300	C_{vL}:p = 0.95
	750	650	-	600	360	C_{vU}: p = 0.95
Ratio R_m/R_e	1.03 4)	1.08		1.15	1.15	C_{vt}: p = 0.90
	-	-	-	1.40	1.50	C_{vU}: p = 0.90
Uniform elongation A_{gt} (%)	1.5	6.0	-	10.0	15.0	C_{vL}:p = 0.90

1) The mechanical properties of Grade 250N material are defined in AS 3679.1
2) See Table 6 Draft 980203
3) The only requirement for d = 4.0 mm is R_e > 500 MPa.
4) Rm/Re = 1.03 for 4.00mm < d > 5.00mm.

The suffix E marks the seismic high ductility grades to be provided in the 300 and 500MPA yield strength category. As can be seen from table 1 all parameters controlling ductility are set tighter for the E-grades if compared to the low ductility (L), normal (N) ductility bars. E.g. the values for the 500Grade define a upper limit for the yield stress at 750MPA for the low ductility (L) bar, 650MPA for the normal (N) bar and 580MPa for the 'E'arthquake bar. Similarly the R_m/R_e Ratio is significantly different with the minimum being 1.05 for the L, 1.10 for the N, and 1.15 for the E grade. Also uniform elongation requirements differ with 1.5% for the L, 6.0% for the N, and 10.0% for the E-Grade.

While the values for the L and N version of the Grade 500 in the to be revised Australian/New Zealand follow the values provided in the EuroNorm Pre-standard ENV 10080, the values for the E grade have been developed from the current edition of NZS 3402[2].

Objective of Testing Programme

Fletcher Challenge Steel Makers (Pacific Steel) has developed a new range of reinforcing bars meeting the requirements of the '**E**'arthquake grades and marketed as "Seismic 300" & "Seismic 500". In order to investigate the weldability of the new 300E and 500E grades, HERA's New Zealand Welding Centre undertook an extensive testing programme covering the MMAW and GMAW processes and most of the common joint configurations used in reinforcement bar assembly. However, also some useful configurations currently not covered in AS1554.3 [3] were to be tested with the view to include them in the newly revised AS/NZS 1554.3. Tests on weldability in cold work areas were also to be undertaken.

WELDING QUALIFICATION TESTS ON GRADE 300E AND GRADE 500E REBARS

In order to meet the requirements for strength, ductility and weldability i.e. preheat requirements, a range of options especially in respect to consumable selection were considered. This included the options for testing rutile type electrodes for the lower strength and lower Carbon Equivalent 300E grade, as well as lower strength electrodes (E55 and W55 with a minimum yield strength requirement of 470MPA) for the 500E grade which may be beneficial in respect to fulfilling the ductility requirements.

Consumable Selection

The consumables listed in Table 2 were tested as shown in relationship with each of the grades.

Table 2: Properties of seismic grade rebars and corresponding consumables tested

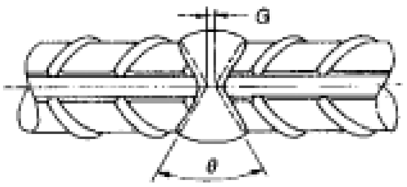
Rebar		MMAW – Electrode	GMAW
Grade	R_e (MPa)	Standard AS/NZS 1553.1	Standard AS2717.1
300E	300	E4112-0 (rutile) E4818 (low hydrogen)	ES6-GC/M-W503AH
500E	500	E6215-B34 E5518	ESD2-GCIM-W559AH

Preheat Requirements

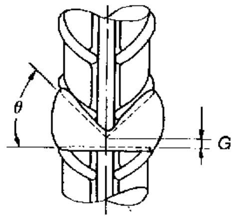
The two E-grade rebars are of the HSLA type with closely controlled chemistry, having a maximum CE of 0.43% for the 300E and 0.49% for the 500E. Following preheat calculations based on WTIA-Technical Note 1 [4] low levels of preheat are required depending on consumable choice (low hydrogen versus rutile) and joint configuration (lap joints versus butt joints) for rebar diameters 32mm and higher. Max. bar diameter tested was 32mm however in order to test the tolerance to cracking in poor weather conditions all weld tests including the 32 mm bars of the programme were performed at rebars cooled down to 0^oC in ice water with subsequent drying by a cloth.

Joint Configurations

The joint configurations as shown in Figure 1 , 2 and 3 were tested. As indicated in the figures some of the joints are currently not covered in AS 1554.3 and have been adopted from AWS D1.4 [5]. Process specific parameters such as angle of preparation or gap dimensions for the joint preparation details have been taken from the standards.



Double V butt splice BD-3a (AS 1554.3)

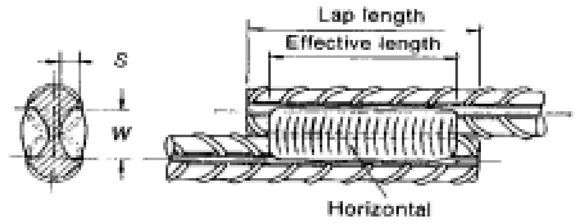


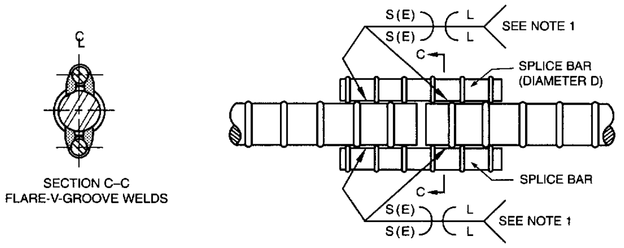
Double-bevel butt splice BD-5 (AS 1554.3)

Figure 1: Butt joint configurations tested

Tests Performed
Standard tests
The following standard tests have been performed

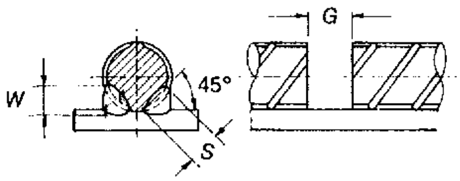
- Butt joints
  - ∗ transverse butt tensile test
  - ∗ transverse guided bend test
  - ∗ macro test (cross section examination)
  - ∗ hardness survey on macro cross section
- Lap joints and indirect butt joints
  - ∗ macro test
  - ∗ transverse tensile test (compliance is not required to current AS1554.3: 1983)
  - ∗ hardness survey on macro cross section
- Plate to reinforcing bar welds
  - ∗ transverse tensile test
  - ∗ macro test

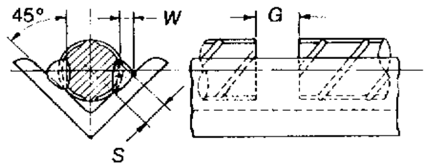




Double lap splice L-a (AS 1554.3)

Indirect butt joint two splice bars
(ANSI / AWS D1.4)

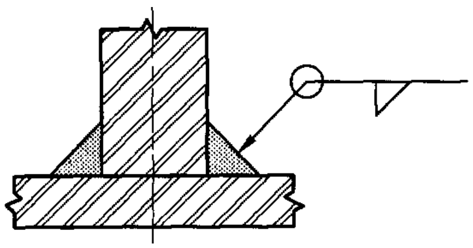


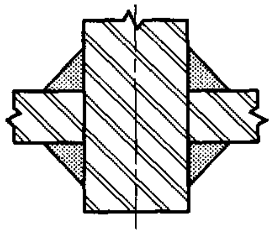


Indirect butt splice with flat backing BI-1a
(AS 1554.3)

Indirect butt splice with angle backing BI-1b
(AS 1554.3)

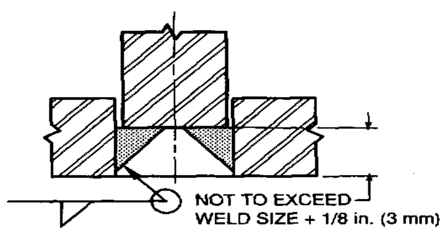
Figure 2: Lap and indirect butt splice configurations

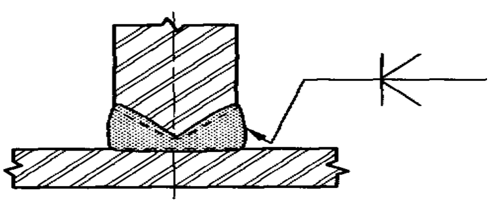




External fillet weld (AWS D 1.4) (a)

External fillet weld to (AWS D1.4) (b)





Internal fillet weld (AWS D1.4) (c)

Complete Penetration Butt Joint
(AWS D 1.4) (d)

Figure 3: Plate to reinforcing bar configurations

Strain age embrittlement test - welding in bent areas
The current AS 1554.3 does not allow welding within 75 mm of any bent portion of the bar which has or had a bend of internal radius less than 6 times the bar size. In order to understand the susceptibility of the E-grades to strain age embrittlement the following tests have been performed.

- A 12 mm rebar is bent to 90° around a 4d former after which there has been made a low energy input (tack type weld) weld of small width in the cold worked area. The bar is then straightened and tensile tested.
- A 32 mm bar is strained in a tensile testing machine to a permanent elongation of 8%. Then the bar is arc striked in the elongated area. After that the bar is tensile tested.
- Bent tests of 32 mm bars to 90° prepared as above with the arc strike in tension are also to be performed.

TEST RESULTS

Butt Joints

Table 3 shows a selection of typical butt joint testing results.[1]

As can be seen from these results the strength and ductility requirements of the parent bar specification are well matched. This includes elongation if it is assumed that uniform elongation is appr. 30% lower than the overall elongation measured. The tensile yield ratio was generally slightly higher than set for the unwelded bar, which was acceptable as no upper limit was set for the welded E-bars.

Table 3: Typical results for butt welded samples

Process	Specimen No E Grade - Bar ϕ -Ident. No.	Electrode Classification	UTS N/mm^2	YS N/mm^2	Tensile/ yield Ratio	Overall Elongation %	Place of Fracture
MMAW	300-32-b1-C	E41 12-0	471	306	1.54	20	HAZ
MMAW	300-32-b16-W	E4818	481	311	1.55	27	55, from weld
MMAW	500-32-b7-W	E6215	647	510	1.27	21	30mm from weld
MMAW	500-32-b8-C	E5518	649	510	1.27	24	40mm from weld
GMAW	300-16-BD3a-F2.1	W50	448	331	1.35	15	Next to HAZ
GMAW	300-24-BD3a-H2.5	W50	458	316	1.45	17	Next to HAZ
GMAW	500-16-BD3a-F2.19	W55	691	534	1.29	18	Next to HAZ
GMAW	500-25-BD3a-H2.23	W55	703	562	1.25	15.5	Next to HAZ

While all Grade 300E bars broke outside the weld in the bar in a ductile failure mode with 45 ° shear surfaces (Figure 4), the Grade 500E bar broke in a mainly ductile mode with ductile shear surface varying between 20 to 70% of the fracture surface (Figure 5).

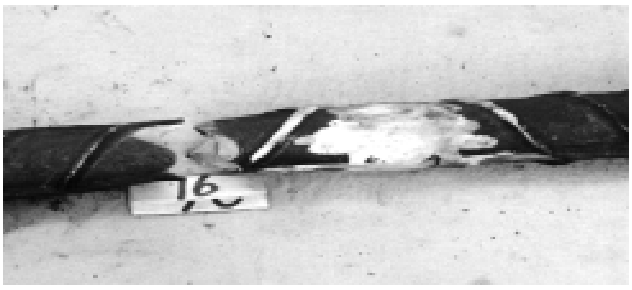


Figure 4: Grade 300E 32mm bar following tensile test

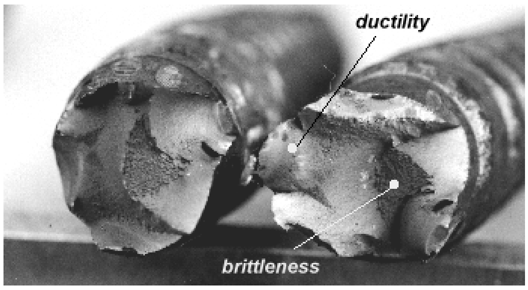


Figure 5: Fracture surface Grade 500E 32mm bar

Using the "under-matched"[2] E55 class electrode (sample MMAW 500-32-b8-c), the tensile test results did not show any difference in performance when compared to the ones welded with the matching E62 class electrode. Macro tests performed showed the weld to be free from noticeable defects and imperfections.

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[1] **Note on elongation**
When analysing the elongation data is has to be noted that the figures shown are overall elongation as described in AS 1391 [6]. The draft standard for reinforcing steels specifies uniform elongation which is measured on a uniformly elongated part of the joint. Uniform elongation as the tests showed is always lower then the values measured for the overall elongation, which is determined by putting the two failed pieces together after the test and measuring over the whole gauge length specified.
[2] The consumable manufacturer lists a typical yield strength of 550MPa which would be matching

The hardness surveys performed showed for the grade 300E bar an average of HV(20)148 for the bar, HV 201 for the weld, and HV 194 for the HAZ. The values for the Grade 500E were HV 221 for the bar, HV 301 for the weld, and HV 233 for the HAZ. There are no requirements set for the hardness in the current Australian or NZ standards, however if compared against acceptable hardness values of other standards and against the fact that the welds were made with low energy input and at low temperature the achieved hardness distribution can be considered as acceptable.

Lap and Indirect Butt SpliceCconfigurations

Table 4 is a selection of typical lap and indirect butt joint test results[3].

Table 4: Typical results for lap and indirect butt splice tests

Joint Type	Process	Specimen No E-Grade - Bar ϕ-Ident. no	Electrode Classifi-cation	UTS N/mm^2	YS N/mm^2	Tensile/ Yield Ratio	Overall Elongation [3] %
Lap joint	MMAW	300-32-L28-C	E4112-0	454	311	1.46	8
Lap joint	MMAW	300-32-129-W	E4818	441	305	1.45	10
Lap joint	MMAW	500-32-L23-C	E5518	547	510	1.07	4
Lap joint	MMAW	500-32-L24-W	E6215	528	509	1.04	4
Indirect butt	GMAW	300-16-BI-1b-V	W50	485	328	1.48	10
splice flat	GMAW	300-24-BI-1b-F	W50	481	318	1.51	14
backing	GMAW	500-16-BI-1b-F	W55	706	537	1.31	5
"	GMAW	500-25-BI-1b-V	W55	709	556	1.27	5
Indirect butt	GMAW	300-16-BI-1a-F	W50	480	328	1.46	13
Splice flat	GMAW	300-24-BI-1a-F	W50	477	305	1.57	19
backing	GMAW	500-16-BI-1a-F	W55	701	542	1.29	7
"	GMAW	500-25-BI-1a-F	W55	590	560	1.05	3

The results indicate a clear relationship of performance to the symmetry of the joint and to Grade and bar diameter tested. While all 300E bars in all joint types tested showed matching strength and ductility values, the 500E bars only showed satisfactory values for the truly symmetric indirect butt joint with two splice bars. While the 500E non symmetric joints delivered the minimum yield strength, they did not in all cases produce the tensile strength required to satisfy the tensile/yield ratio set and the elongation requirement. The indirect butt splice with angle backing satisfied the tensile yield ratio for both diameters tested, however ductility for the 25 mm bar was low with 5% overall elongation measured. This also applied for the indirect butt splice with the flat bar backing were tensile/yield ratio and elongation were unsatisfactory for the 25 mm bar.

Figure 6 shows the 500E lap splice sample after testing. Cracks at the weld ends appeared after yield was reached with one bar the suddenly fracturing in a mainly brittle manner (Figure 7).

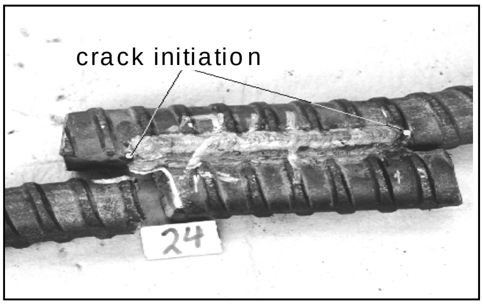

Figure 6: Lap joint sample MMAW 500E - MMAW 500E - 32 mm bar

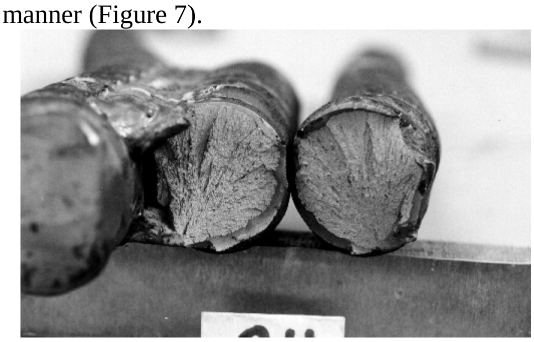

Figure 7: Fracture surface of lap joint sample MMAW 500E - 32 mm bar

[3] **Note on elongation**
If measuring overall elongation particularly on non symmetric joints such as the lap joint not only are there more than one area which elongate, the joints also distort angularly during testing and the value measured as overall elongation is considerably than the actual elongation of the welded joint.

Plate to Reinforcing Bar Configurations

Table 5 shows selected results of the plate to reinforcement bar joint alternatives tested.

Table 5: Tensile test results of plate to reinforcing bar joint alternatives tested

Joint Type	Process	Specimen No E-Grade - Bar ϕ-Ident. No	Electrode	UTS N/mm^2	YS N/mm^2	Tensile/ Yield Ratio	Overall Elongation %
External Fillet a)	MMAW	300-16-AWSD1.4a-V-2.37	E4113	482	323	1.49	22
	MMAW	300-16-AWSD1.4a-H-2.40	E4113	479	312	1.54	29
	MMAW	500-16-AWSD1.4a-V-2.53	E6215	702	547	1.28	11
	MMAW	500-25-AWSD1.4a-H-2.56	E6215	708	558	1.27	12
External Fillet b)	MMAW	300-16-AWSD1.4b-V-2.41	E4113	482	323	1.49	29
	MMAW	300-24-AWSD1.4b-V-2.43	E4113	481	309	1.55	40
	MMAW	500-16-AWSD1.4b-V-2.57	E6215	712	547	1.3	20
	MMAW	500-25-AWSD1.4b-V-2.59	E6215	711	550	1.29	21
Internal Fillet	MMAW	300-16-AWSD1.4c-V-2.45	E4113	480	320	1.5	30
	MMAW	300-24-AWSD1.4c-V-2.47	E4113	480	314	1.53	20
	MMAW	500-16-AWSD1.4c-V-2.61	E6215	694	542	1.28	26
	MMAW	500-25-AWSD1.4c-V-2.63	E6215	712	555	1.28	30
CP Butt Joint	MMAW	300-16-AWSD1.4d-V-2.49	E4113	482	324	1.49	31
	MMAW	300-24-AWSD1.4d-V-2.51	E4113	480	312	1.54	32
	MMAW	500-16-AWSD1.4d-V-2.65	E6215	702	547	1.28	9
	MMAW	500-25-AWSD1.4d-V-2.67	E6215	716	560	1.28	24

For both the 300E and the 500E the requirements set for the qualification of the welds in respect to strength and elongation have been met.

Figure 8 shows the macro of the internal fillet weld alternative welded in the vertical position with the bar horizontal. It demonstrates the presence of some slag inclusions in the root area. This was typical for this type of joint as access of the root is difficult to achieve especially when welding in position.

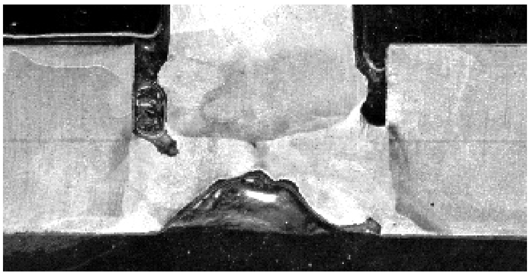

Figure 8: Macro of internal fillet weld alternative of plate - reinforcement bar joint

DISCUSSION

Overall the tests showed that the performance of the welded joints in respect to strength and elongation meet the requirements set out for the welding of seismic grade reinforcement bars. However there is one noticeable exception relating to the ductility requirement for non symmetric joints. As shown in Figure 6 with the non symmetric lap joint, as a result of the developed moment of the out of alignment bars, cracks would develop a the stop/starts of the welds in the higher strength grade 500E, with the welds suddenly fracturing above the required yield strength but below the expected tensile load in a mainly brittle mode. With a drop in achieved overall elongation to the order of 4-5% it can also be argued that this level of elongation may not be sufficient for the intended earthquake performance.

If the lap splice joint is changed to an indirect butt splice with two splice bars as shown in Figure 9 tensile/yield ratio as well as elongation was as expected. The alternatives of indirect butt joints using an angular or plate backing performed better than the standard lap splice, however especially for the larger diameter bars the sizing of the angle or the plate become critical in order to avoid joint rotation. This is a significant result, which needs to be considered when specifying joints for seismic applications.

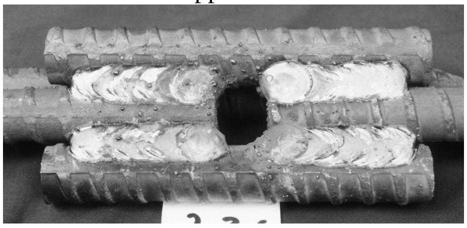

Figure 9: Indirect butt splice with two splice bars

As expected butt joints with symmetric load application performed very well with good ductility and met the requirement for minimum tensile/yield ratio. This was also true for the two lower strength electrodes tested with each of the two grades. As all joints failed well outside the weld area the electrode influence on the tensile strength was not noted, there was also no noticeable difference in elongation or tensile/yield ratio.

The Pacific Steel 300E and 500E Grade showed no performance reduction when a 12 mm diameter bar was arc striked on a 8% cold worked area indicating little susceptibility for strain age embrittlement. However, while performing general bending tests, it was noted that a 500E bar bent to 90° in the large 32mm diameter following the bending radius rules for the lower strength grades, could not be straightened without cracking. It appears that for the new 500 Grades provisions for thickness related bending radius adjustments need to be made in order to avoid cracking problems independent from the welding operation. However for the qualification of welding procedures recommendations on the bending requirements of welded bars should also be clarified.

Also interesting was the performance of some of the more unusual joint alternatives currently not covered in AS1554.3. As noted the indirect butt slice with two splice bars (Figure 9) performed excellent. Adapted from AWS D1.4, four variations of welding reinforcing bars in a T arrangement against or through a flat plate were tested as shown in Figure 3. All of those plate to reinforcing bar joints performed well in respect to strength and ductility. However a note of caution is advisable on the ability to consistently achieve the required weld quality for the joint alternative d internal fillet weld to AWS D1.4 (see Figure 9). The difficulty of weld access particularly in position makes reliable fusion very dependent on a high degree of welder skill.

CONCLUSIONS

Welding Grade 'E" reinforcing bars will provide the expected performance in respect to plastic deformation capacity and strength under severe earthquake loading provided the adequate procedures are followed. It is important that welding joint selection is suitable for seismic application as is the choice of welding consumables.
Welding with the MMAW process using low hydrogen electrodes places no or only low preheat requirements on the welding of the Pacific Steel 'E' grade bars in the thickness range of up to 25 mm. This makes this process very suitable for on site welding, however the no preheat requirement also applies for the GMAW process typically used in the workshop environment.
As the strain-age embrittlement tests showed, welding in cold formed areas does not appear to be a problem for the Pacific Steel E grade bars. However further research is recommended on the aspect of bending especially of the 500 grades. Bar thickness related values for bending and reverse bending of unwelded and welded bars should be provided as bending is not an uncommon practice found on building sites.
As a result of the extensive testing performed a comprehensive range of qualified procedures for MMAW and GMAW welding of the two Pacific Steel "E" grade bars are available and product users can obtain copies of the procedures from HERA's New Zealand Welding Centre.

REFERENCES

[1] DR 98 119 Steel reinforcing material (Revision and amalgamation of AS 1302-1991, AS1303-1991,AS1304-1991, NZS 3402:1989, NZS 3421:1975 and NZS 3422:1975), Standards Australia
[2] NZS 3402:1989, Steel bars for the reinforcement of concrete, Standards New Zealand
[3] AS 1554.3.3-1983, Structural Steel Welding Code Part 3: Welding of Reinforcing Steel, Standards Australia
[4] WTIA Technical Note 1; The Weldability of Steels; Welding Technology Institute of Australia
[5] ANSI/AWS D1.4-98, Structural Welding Code - Reinforcing Steel, American Welding Society
[6] AS 1391-1991, Method for Tensile Testing of Metals, Standards Australia