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DUCTILITY MEASUREMENTS OF THIN G550 SHEET STEELS

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SUMMARY

Cold formed structural members are fabricated from sheet steels which must meet various material requirements prescribed in applicable national design standards. These requirements ensure that; 1) stress concentrations can be redistributed and 2) members and connections can undergo a minimum amount of displacement without a loss in structural performance. The Australian / New Zealand, AS/NZS 4600, and both North American, CSA-S136 and AISI, Cold Formed Steel Design Standards allow for the use of thin (t < 0.9mm), high strength (f_y = 550MPa) sheet steels if the yield stress and ultimate strength are reduced to 75% of their minimum specified values. This paper provides a summary of results detailing the ductility and net cross-section tensile resistance of G550 sheet steels (to Australian Standard AS 1397) tested as solid and perforated coupons. Material properties of the test specimens are compared with the Dhalla and Winter requirements for ductility and ultimate strength to yield stress ratio. Limit states tensile design equations are calibrated according to procedures defined by the American Iron and Steel Institute (AISI) Commentary.

1 INTRODUCTION

G550 sheet steels *(SA, 1993)* are manufactured by cold reducing mild sheet steels ($f_y \approx$ 300MPa) to a thickness which ranges from 0.42mm to 1.0mm. Cold reduction produces large deformations of the grain structure which cause an increase in yield stress and ultimate strength and a decrease in ductility. G550 sheet steels (0.48mm $\leq t \leq$ 0.75mm) have recently been introduced for use as structural members in the Australian residential construction industry, as well as for panel and deck sections in other types of building construction *(Hancock and Murray, 1996)*. The use of G550 sheet steels has been restricted to non-structural applications in most countries due to concerns regarding the ductility of members and connections.

Cold formed structural members are fabricated from sheet steels consisting of various material properties which must meet requirements prescribed in applicable design standards. The Australian / New Zealand Design Standard *(SA/SNZ, 1996)* allows for the use of thin (t < 0.9mm), high strength (f_y = 550MPa) sheet steels in all structural sections. However, due to the lack of ductility exhibited by sheet steels which are cold reduced to thickness, the engineer must use a yield stress and ultimate strength reduced to 75% of the minimum specified values. The American Iron and Steel Institute (AISI) Design Specification *(1997a)* further limits the use of thin, high strength steels to roofing, siding and floor decking panels. Sheet steels are required to have a minimum elongation capability to ensure that members and connections can undergo small displacements without a loss in structural performance, and to reduce the harmful effects of stress concentrations. The ductility criterion specified in the Australian / New Zealand and North American *(CSA, 1994; AISI, 1997a)* Design Standards is based on an investigation of sheet steels by Dhalla and Winter *(1974a,b)*, which did not include the thin high strength G550 steels available

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today. However, Dhalla and Winter did test commercially available low ductility steel (A446 Grade E *(1968)* in 0.965mm thickness - type Z) which did not satisfy their elongation requirements, but was able to fully plastify for perforated longitudinal test specimens and reach 94% of the net cross-section tensile strength for transverse specimens.

This paper reports on the test results of solid and perforated tensile coupons, as well as the calibration of tensile equations for use in limit states design standards. Sheet steels which range in base metal thickness from 0.40 to 0.60mm were tested as tensile coupons with various size and shape perforations. The material properties of cold reduced steels have been shown to be anisotropic *(Dhalla and Winter, 1974a,b; Wu et al. 1995)*, hence, when possible, coupons were cut from four directions within the sheet; longitudinal, transverse, diagonal right, and diagonal left with respect to the rolling direction. This array of coupon directions was used to determine the degree of anisotropy and its effect on ductility and structural behaviour. Measurements of local and uniform elongations were completed using a fine gauge length grid (2.5mm c/c) marked on the surface of the test specimens. Perforated specimen test results were used to determine the ability of the sheet steel to redistribute stress concentrations throughout the cross-section, to find out if the net cross-sectional strength can be developed and to calibrate the limit states tensile design equations. The elongation and net cross-section capacity of the tested steels are compared with the Dhalla and Winter *(1974b)* requirements, and a liberalisation of the 75% rule is suggested for these steels. A more detailed description of the results summarised in this paper can be found in Rogers and Hancock *(1996)*.

2 Dhalla and Winter

Dhalla and Winter *(1974a,b)* completed an investigation into the ductility of cold formed sheet steels, which has provided a basis for material specifications set out in current cold formed steel design standards. The overall objective of the Dhalla and Winter investigation was to study the use of low carbon, low ductility, high strength steels for cold formed structural members. Dhalla and Winter focused their research on the effect of ductility, i.e. gauge length elongation, and the ratio of ultimate strength to yield stress, f_u / f_y, on the behaviour of cold formed steel members and connections under static tensile loading. Two measurements of ductility are required to; 1) characterise uniform straining during strain hardening and 2) characterise localised elongation of the fracture zone, i.e. the downward branch of the stress/strain curve *(Dhalla and Winter, 1974b)*. Dhalla and Winter found that true uniform strain and true necking strain are difficult to obtain, due to problems with calculating the reduced area of the thin tensile coupons during testing. Similarly, the authors found it difficult to accurately measure the reduced thickness of the thin G550 sheet steels, hence, gauge length elongations are used to provide approximate measures of ductility in this paper.

Based on the results of their ductility investigation Dhalla and Winter *(1974b)* recommended that sheet steels must possess adequate uniform ductility, $\varepsilon_U \geq 3\%$, to fully plastify the net cross-section and to distribute stress over the net area at perforations or other stress raisers. A minimum local elongation capability, $\varepsilon_L \geq 20\%$, over a 12.7mm gauge length was suggested to ensure ductile failure, i.e. to avoid sudden brittle fracture of structural members. These recommendations, with only slight modifications, are incorporated into the specifications of many cold formed steel design standards in existence today, in lieu of the standard 50mm overall elongation requirement, $\varepsilon_{50} \geq 10\%$.

Dhalla and Winter *(1974a,b)* also investigated the work of Unwin *(1903)* and Oliver *(1928)* on the relationship between gauge length and cross-sectional area. Unwin observed that uniform elongation takes place along the entire gauge length prior to reaching the ultimate load, and hence, is a function of the length of the gauge, whereas local elongation occurs after the ultimate load is obtained and is a function of the cross-sectional area. Oliver proposed a logarithmic relationship between percent elongation and $L / A^{1/2}$, where L is the gauge length and A is the cross-sectional area. Dhalla and Winter reported that for low ductility steels Unwin's and Oliver's equations are nearly the same. The elongation measurements for tensile specimens which are milled to the same coupon size, but have different thicknesses, may not be comparable because $L / A^{1/2}$ is not held constant.

3 G550 Sheet Steels

The steels investigated as a part of this paper were manufactured using a process called cold reduction, which can be used to increase the strength and hardness, as well as produce an accurate thickness for sheet steels and other steel products. This process causes the grain structure of cold reduced steels to elongate in the rolling direction, which produces an increase in strength and a decrease in ductility. The effects of cold working are cumulative, i.e. grain distortion increases with further cold working, however it is possible to change the distorted grain structure and control the steel properties through subsequent heat treatment. Various types of heat treatment exist and are used for different steel products. G300 sheet steels are fully recrystallised, i.e. the grain structure is returned to its original state, although some preferred grain orientation remains, whereas G550 sheet steels are stress relief annealed, i.e. recrystallisation does not occur. Stress relief annealing involves heating the steel to below its recrystallisation temperature, holding the steel until the temperature is constant throughout its thickness, then cooling slowly. Annealing is carried out in the hot dip coating line prior to application of either a zinc or aluminum/zinc coating. The G550 sheet steels used in this research must be differentiated from other sheet steels whose high yield stress and ultimate strength values are obtained by means of an alloying process, i.e. high strength low alloy (HSLA) steels.

The material property requirements for G300 or similar mild sheet steels and G550 or Grade E sheet steels are specified in Australia by AS 1397 *(1993)* and in North America by the following ASTM Standards; A611 *(1994)*, A653 *(1994)* and A792 *(1994)*. Material property specifications for HSLA sheet steels can be found in ASTM Standard A653.

4 Tensile Coupon Tests and Results

4.1 General

Three hundred and seventy tensile specimens were tested in the J.W. Roderick Laboratory for Materials and Structures at the University of Sydney. The main objectives of this experimental testing phase were to evaluate the Dhalla and Winter *(1974b)* material requirements and to determine the effect of various size and type perforations on G550 sheet steels. Seven different types of sheet steels were tested, including 0.60mm G300, and used as a basis for comparison with the current material property requirements specified in the Australian / New Zealand *(SA/SNZ, 1996)* and North American *(CSA, 1994; AISI 1997a)* Cold Formed Steel Design Standards. All steels were cold reduced to thickness, with an aluminum/zinc alloy (zincalume - AZ), or zinc (Z) coating and obtained from standard coils during normal rolling operations.

Circular holes were concentrically drilled in the tensile coupons, while square and diamond shape holes were concentrically punched in test coupons to identify the effect of various shape perforations on structural performance. Circular perforations with nominal diameters of 1.0, 2.0, 5.0 and 7.0mm were used, resulting in net cross-sectional areas of 92, 84, 60 and 44% of the gross cross-sectional area, respectively. Square and diamond shape holes were sized with 60% of the gross cross-section remaining to facilitate comparison with the 5.0mm diameter circular perforations (see Fig. 1).

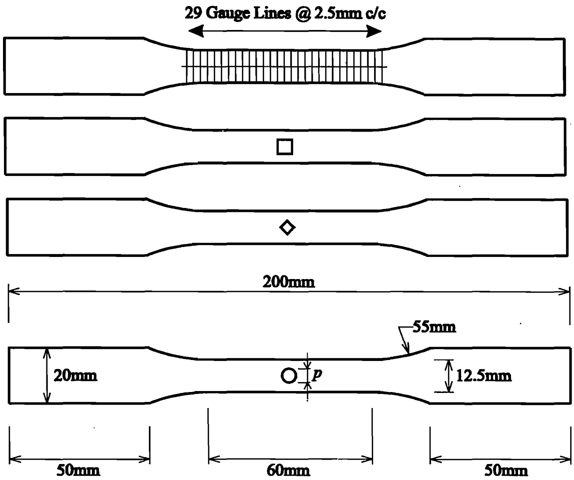

Fig. 1 Solid and Perforated Tensile Coupons

4.2 Basic Material Properties

The basic material properties, i.e. yield stress, ultimate strength, and Young's modulus were obtained through the tensile testing of coated coupons according to ASTM A370 *(1994)* recommendations. Material properties calculated using the base metal thickness are given in Table 1 for both the static and dynamic conditions. The cross-head of the test frame was stopped periodically for one minute intervals during the testing of solid coupon specimens to determine the static yield stress and static ultimate strength values of the sheet steels. During these stoppages the position of the cross-head was maintained while the load applied to the test specimen decreased dependent on the dynamic effect of the strain rate used during testing.

The material properties for the 0.42 and 0.60mm G550 sheet steels (042-G550, 060-G550) are dependent on the direction from which the coupons were cut. Yield stress and ultimate strength values are significantly higher for specimens obtained from the transverse direction, in comparison to specimens obtained from the longitudinal and diagonal directions. It was not possible to determine if the material properties for New Zealand sheet steels vary with direction because only longitudinal test specimens were available. The material properties of the G300 sheet steel are not dependent on direction within the plane of the sheet.

All G550 sheet steels tested for this paper yielded gradually with minimal strain hardening, whereas the G300 sheet steels displayed a sharp yield point, followed by a yield plateau then a strain hardening region. Yield stress values for the G550 sheet steels were calculated using the 0.2% proof stress method. The lack of a strain hardening range for the G550 materials is indicated by the consistent ultimate strength to yield stress ratios, f_u / f_y, of unity. The G550 sheet steels do not meet the Dhalla and Winter *(1974b)* or current design standard requirements for ultimate strength to yield stress ratio, $f_u / f_y \geq 1.08$.

Table 1 Material Properties of Sheet Steels (Mean Values)

Specimen Type	*Direction*	t_b (mm)	P_f / P_t	f_y^a (MPa)	f_u^a (MPa)	f_u / f_y^a	E (MPa)
042-G550	*Longitudinal*	0.41	0.81	681/658	681/658	1.00/1.00	219000
	Transverse	0.41	0.93	768/745	768/745	1.00/1.00	252000
	Diagonal Right	0.41	0.75	668/645	668/645	1.00/1.00	192000
	Diagonal Left	0.41	0.74	673/650	673/650	1.00/1.00	193000
060-G550	*Longitudinal*	0.59	0.72	703/686	703/686	1.00/1.00	214000
	Transverse	0.59	0.66	785/767	785/767	1.00/1.00	236000
	Diagonal	0.59	0.68	707/690	707/690	1.00/1.00	203000
060-G300	*Longitudinal*	0.58	0.78	368/348	431/411	1.17/1.18	202000
	Transverse	0.58	0.78	381/360	428/408	1.12/1.13	210000
	Diagonal	0.58	0.84	376/356	437/417	1.16/1.17	218000
NZ 040-G550	*Longitudinal*	0.40	0.80	732/713	732/713	1.00/1.00	237000
NZ 040W-G550	*Longitudinal*	0.40	0.82	692/663	692/663	1.00/1.00	224000
NZ 055-G550	*Longitudinal*	0.55	0.72	774/758	774/758	1.00/1.00	229000
NZ 055W-G550	*Longitudinal*	0.55	0.76	685/668	685/668	1.00/1.00	214000

Note: Material properties were calculated using the base metal thickness.
[a] *Dynamic/Static* values given.

4.3 Young's Modulus of Elasticity

Young's modulus of elasticity was calculated for each strain gauged specimen included in this investigation (see Table 1). Tests of G550 sheet steel tensile specimens cut from the longitudinal direction result in Young's moduli with values between 214 and 237GPa, i.e. E values determined using the base metal thickness. Young's modulus increases for test specimens obtained from the transverse direction, e.g. 252GPa for 042-G550 sheet steels, and decreases for test specimens obtained from the diagonal directions, e.g. 192GPa for 042-G550 sheet steels. The results of G300 sheet steel specimens show that Young's modulus is also dependent on direction for fully recrystallised steels, because of the inability of the grain structure to return to a completely random orientation even after heat treatment.

Young's modulus is dependent on direction for stress relief annealed sheet steels cold reduced to thickness because of the large distortions in the crystal structure caused by the rolling procedure used in the manufacturing process. With cold reduction the original random distribution of grains becomes oriented in line with the rolling direction. Van Vlack *(1984)* lists maximum, minimum and random Young's moduli for a crystal of iron as 280, 125 and 205GPa, respectively. The value of Young's modulus determined from a tensile coupon is dependent on the number of grains which exceed their yield stress during straining, and hence the orientation of grains with respect to the direction of loading.

4.4 Comparison of Solid Fracture-to-Ultimate Load Ratios

The ratio of fracture-to-ultimate load, P_f / P_t, can be used to indicate the amount of local straining which occurs after the tensile specimen has reached its ultimate load carrying capacity, i.e. the lower the P_f / P_t ratio the greater the degree of ductility (see Table 1). All solid tensile test specimens, except for transverse 042-G550 coupons, exhibit fracture-to-ultimate load ratios within a range that shows acceptable levels of deformation prior to final fracture, i.e. the P_f / P_t ratios calculated for the mild G300 solid tensile coupons included in this report define an acceptable range. In many instances the decrease in fracture load from ultimate for G550 tensile specimens was greater than that experienced by the mild 060-G300 sheet steels. The transverse 042-G550 tensile specimens fail suddenly soon after the ultimate load is reached without significant warning or necking of the test specimen.

4.5 Gauge Length Elongation

Measurements of overall, local and uniform elongations were completed using a fine gauge length grid marked on the surface of the test specimens (see Fig. 1). Gauge line measurements were used to determine the elongation of each 2.5mm gauge length marked on the test coupons. These individual gauge length measurements were combined to calculate values for the various elongation types (see Fig. 2).

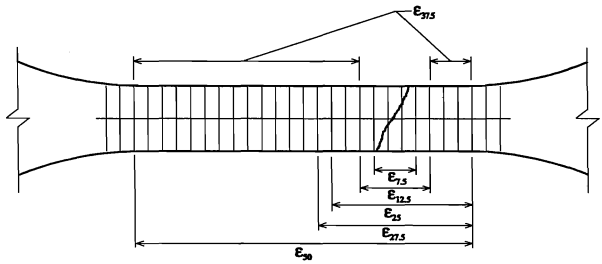

Fig. 2 Gauge Length Measurements

Table 2 Coated Gauge Length Elongation Measurements (Mean Values)

Specimen Type	*Direction*	ε_{50} (%)	$\varepsilon_{12.5}$ (%)	$\varepsilon_{37.5}$ (%)	ε_{25} (%)	$\varepsilon_{27.5}$ (%)	$\varepsilon_{7.5}$ (%)
042-G550	*Longitudinal*	4.61	7.04	3.75	5.86	5.66	9.47
	Transverse	0.82	3.03	0.18	1.60	1.41	4.91
	Diagonal Right	3.54	12.5	0.94	6.95	6.33	17.4
	Diagonal Left	4.05	14.8	0.49	7.81	7.16	19.3
NZ 040-G550	*Longitudinal*	2.07	7.22	0.51	3.88	3.55	10.5
NZ 040W-G550	*Longitudinal*	2.22	7.19	0.58	3.93	3.58	11.5

Specimen Type	*Direction*	ε_{50} (%)	$\varepsilon_{12.5}$ (%)	$\varepsilon_{37.5}$ (%)	ε_{30} (%)	$\varepsilon_{32.5}$ (%)	$\varepsilon_{7.5}$ (%)
060-G550	*Longitudinal*	5.59	10.5	3.93	7.09	6.89	14.6
	Transverse	1.78	5.71	0.47	2.79	2.62	9.07
	Diagonal	3.56	11.7	0.82	5.64	5.23	17.4
060-G300	*Longitudinal*	24.3	38.5	19.5	27.7	27.1	48.9
	Transverse	27.4	46.0	21.3	32.7	31.8	55.6
	Diagonal	24.2	35.9	20.3	27.2	26.7	42.9
NZ 055-G550	*Longitudinal*	2.03	7.66	0.19	3.33	3.06	12.2
NZ 055W-G550	*Longitudinal*	3.29	9.70	1.31	5.16	4.84	13.1

Elongation measurements for the different sheet steels, with specimens from the four directions, were obtained from 78 solid tensile coupons (see Table 2). These measurements were used to determine the standard 50mm gauge length elongation, ε_{50}, along with the Dhalla and Winter *(1974b)* recommended local (12.5mm length across the fracture zone, $\varepsilon_{12.5}$) and uniform (37.5mm length excluding the fracture zone, $\varepsilon_{37.5}$) gauge length elongations. The measured gauge lengths were also modified according to the $L / A^{1/2}$ relationship developed by Unwin *(1903)* and Oliver *(1928)*. The modified gauges, i.e. 25, 27.5, 30 and 32.5mm, were used in an attempt to replace the overall 50mm gauge length measurement typically presented for ductility evaluation. Local elongation gauge lengths were also modified to ensure an $L / A^{1/2}$ ratio consistent with the Dhalla and Winter data, i.e. a 7.5mm gauge length in place of the 12.5mm gauge length.

4.6 Modified Gauge Length Comparison

The G550 sheet steels tested as part of this investigation do not have adequate ductility to meet the overall elongation requirement, $\varepsilon_{50} \geq 10\%$, specified by current design standards *(SA/SNZ, 1996; CSA, 1994; AISI, 1997a)*. However, the fully annealed G300 test specimens possess adequate ductility according to the same design standards. The elongation capability of the G300 sheet steel is not direction dependent, in contrast to the G550 sheet steels which have limited ductility when tested in the transverse direction. Longitudinal G550 sheet steel specimens provide the greatest amount of ductility compared with both the diagonal and transverse test specimens. However, the sheet steels obtained from New Zealand do not exhibit the same degree of ductility in the longitudinal direction in comparison with the 042 and 060-G550 sheet steels. It is also noted that elongation capability increases with an increase in thickness for most sheet steel types.

Similarly, the G550 sheet steels do not meet the Dhalla and Winter *(1974b)* local elongation requirements, $\varepsilon_L \geq 20\%$ in a 12.5mm gauge length, whereas the G300 sheet steels have sufficient ductility. Again the G550 test specimens cut from the transverse direction result in the lowest measured elongation, with elongation in the diagonal and longitudinal directions significantly higher. The New Zealand sheet steels produce elongation measurements similar to those determined for the 042 and 060-G550 longitudinal specimens.

G550 sheet steels obtained from the longitudinal direction have a greater ability to elongate uniformly along the entire gauge length. The 042 and 060-G550 test specimens exceed the uniform elongation requirement, $\varepsilon_U \geq 3\%$, as do the G300 test specimens. However, the New Zealand G550 longitudinal specimens do not possess this same degree of elongation ability. The 040, 040W, 055 and 055W-G550 New Zealand sheet steels, as well as the other transverse and diagonal G550 test specimens do not have adequate ductility to meet the uniform elongation requirements.

Overall elongation measurements for the adjusted gauge lengths, i.e. ε_{25}, $\varepsilon_{27.5}$, ε_{30} and $\varepsilon_{32.5}$, reveal that the G550 sheet steels still do not meet the 10% ductility requirement, even though the $L / A^{1/2}$ ratios are comparable to those calculated for the Dhalla and Winter *(1974a)* data, i.e. $L / A^{1/2} \approx 11$. The adjusted local gauge length measurements also do not meet the Dhalla and Winter required elongation values, although the measurements obtained from specimens in the diagonal direction show significant improvement.

4.7 Distribution of 2.5mm Gauge Length Elongation

The percent elongation of each 2.5mm gauge was calculated based on its original measured length, and then graphed to show the extent and location of elongations over the entire gauge length. The elongation distribution graphs for the 78 test specimens can be found in Rogers and Hancock *(1996)*, while four representative elongation distribution graphs for 042-G550 and 060-G300 sheet steels are presented in Fig. 3.

An estimate of the amount of local and uniform elongation can be determined by viewing the elongation distribution graphs. In general, G550 coated longitudinal specimens have constant uniform elongation for each 2.5mm gauge with an increase in percent elongation at the gauge in which fracture occurs. Transverse G550 specimens show almost no uniform elongation, but do

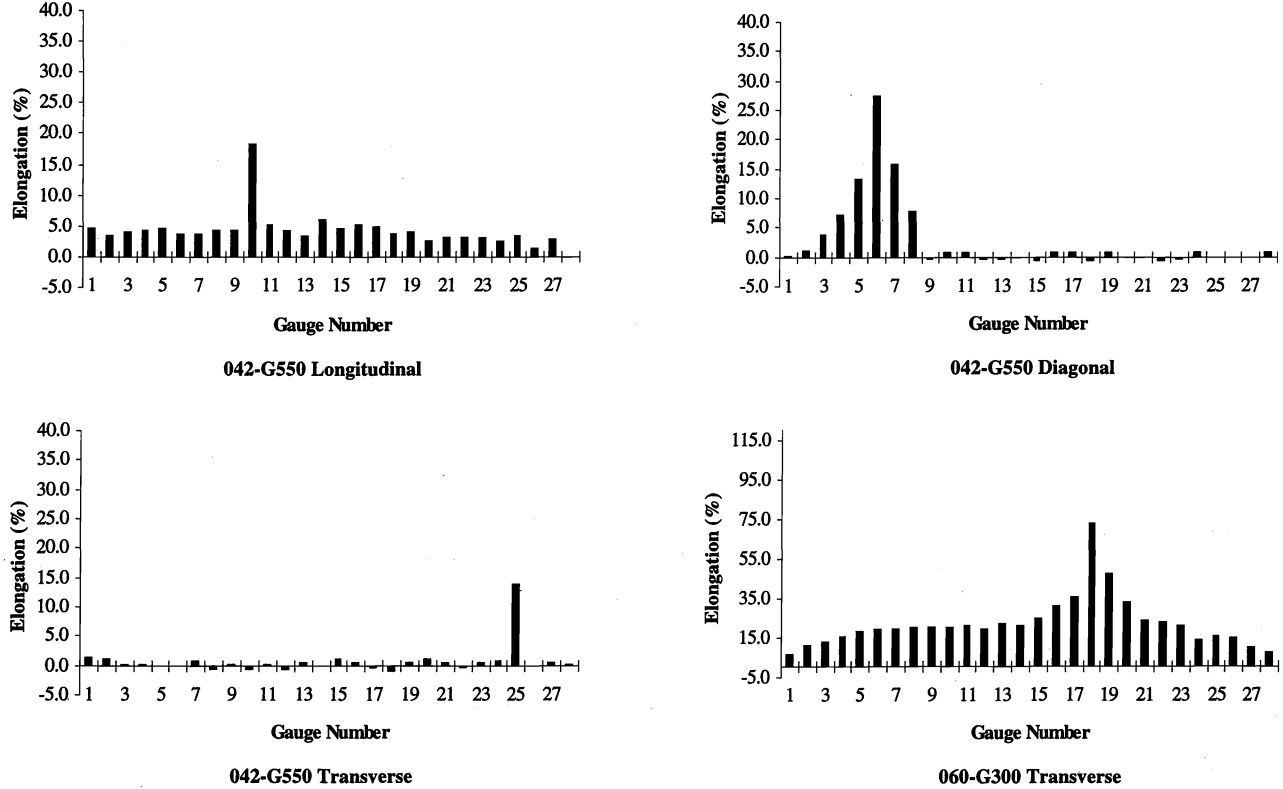

Fig. 3 2.5mm Gauge Length Elongation Distribution

have limited elongation at the fracture. Graphs of G550 diagonal test specimen results indicate that uniform elongation is limited outside of a 12.5mm zone around the fracture, while local elongation occurs in the fracture gauge, as well as in the adjoining gauges. These results show that the distribution of gauge elongations for thin G550 sheet steels is dependent on the direction from which the tensile coupons are obtained, however the thickness of the material does not affect the distribution of elongation for the range of thicknesses tested.

In contrast, the G300 sheet steel tensile specimens have an elongation distribution which is independent of the direction from which the coupons are cut. Uniform elongation occurs in each 2.5mm gauge length with a more gradual increase in elongation for gauges close to the fracture.

4.8 Perforated Tensile Tests

Perforated tensile tests were completed to; 1) understand the effect of stress concentrations on the ultimate tensile strength of G550 sheet steels, 2) evaluate the ability of G550 sheet steels to redistribute stress concentrations over the cross-section and 3) determine if the net cross-section can be fully developed under tensile load. Dynamic ultimate test loads, P_t, were used in comparison with predicted ultimate tensile strengths, P_p, given by Eq. 1. All perforated tensile specimens failed by fracture of the net cross-sectional area at the perforation. For this reason the predicted ultimate tensile strengths listed are based on the ultimate strength of the net cross-section and not on yielding of the gross cross-section.

$$P_p = A_{bn} f_u' \qquad (1)$$

where A_{bn} is the base metal net cross-sectional area and f_u' is the corresponding average dynamic ultimate strength calculated using the base metal thickness. The Australian / New Zealand *(SA/SNZ, 1996)*, Canadian *(CSA, 1994)* and European *(Eurocode, 1996)* Design Standards all define the nominal ultimate tensile strength at fracture as given in Eq. 1. However, this formulation is not contained in the draft edition of the AISI Specification *(1997a)*, although, AISI ballot C/S96-66B *(1996)*, which is currently under review by the AISI Specification Committee, does present the nominal ultimate tensile strength at fracture as shown in Eq. 1.

The influence of an aluminum/zinc or zinc coating on the overall behaviour of sheet steels was accounted for by using coated specimens for both the perforated tensile tests and the material property tests. The change in material properties due to the coating is incorporated into the design process by using the ultimate tensile loads from tests of coated coupons. Table 3 lists mean values and statistical data of the test-to-predicted results for all of the perforated specimens grouped into categories depending on direction and sheet type, i.e. all hole sizes and shapes are included in the number given for each mean and statistical value.

The statistical results indicate that for concentrically perforated tensile coupon tests using G550 sheet steels it is possible to develop the full net cross-section and to redistribute stress concentrations, i.e. P_t / P_p > 1.0. In only two instances do the mean test-to-predicted ratios fall marginally below unity, i.e. for transverse 060-G550 (0.994) and longitudinal 040W-G550 (0.986) test specimens. A high degree of consistency in test results is indicated by the low calculated standard deviations and coefficients of variation.

Tensile behaviour is dependent on the direction in which the test specimens are oriented, that is test-to-predicted values are lowest in the transverse direction for the G550 sheet steels. Tensile specimens from the longitudinal and diagonal directions provide test values which exceed those in the transverse direction in all cases except for the 060-G300 sheet steel specimens. No distinct advantage is evident for the 0.60 and 0.55mm sheet steels over the 0.42 and 0.40mm sheet steels, i.e. the test-to-predicted ratios for the thicker sheet steels are not greater than those for the thinner sheet steels. The rolling process and extent of cold reduction for the different thickness sheet steels is comparable, hence the marginal difference in thickness does not cause a dramatic change in tensile behaviour. The net cross-section ultimate tensile strength can be adequately predicted using current design provisions.

Table 3 Statistical Results of Perforated Test-to-Predicted and Fracture-to-Ultimate Loads

Specimen Type	*Direction*	*# Tests*	*Mean* P_f / P_t	*Mean* P_t / P_p	*S.D.* P_t / P_p	*C.o.V.* P_t / P_p
042-G550	*Longitudinal*	18	0.33	1.024	0.033	0.034
	Transverse	18	0.94	1.015	0.027	0.029
	Diagonal Right	18	0.42	1.028	0.030	0.031
	Diagonal Left	18	0.41	1.018	0.030	0.031
060-G550	*Longitudinal*	18	0.25	1.010	0.012	0.013
	Transverse	18	0.33	0.994	0.018	0.019
	Diagonal	18	0.35	1.005	0.014	0.015
060-G300	*Longitudinal*	17	0.0	1.020	0.018	0.019
	Transverse	18	0.0	1.036	0.018	0.018
	Diagonal	18	0.0	1.027	0.015	0.016
NZ 040-G550	*Longitudinal*	18	0.53	1.032	0.040	0.041
NZ 040W-G550	*Longitudinal*	18	0.33	0.986	0.024	0.026
NZ 055-G550	*Longitudinal*	18	0.42	1.005	0.026	0.028
NZ 055W-G550	*Longitudinal*	18	0.35	1.002	0.010	0.010

Note: Material properties were calculated using the base metal thickness.

4.9 Comparison of 5mm Circular, Square and Diamond Shape Perforations

An evaluation of the ability of G550 sheet steels to redistribute various types of stress concentrations was completed by testing three different types of concentrically placed perforations. The three types of holes (circular, square and diamond) have the same nominal net cross-sectional area, with small variations due to fabrication tolerances. The net cross-section is approximately 60% (circular and square) and 62% (diamond) of the original gross cross-sectional area, however the actual amount of material parallel to the load which is subjected to a stress concentration is dependent on the type of perforation. Test specimens with circular and diamond shape holes have a very short length over which the stress is at a maximum value, whereas square holes experience a maximum stress over a 5mm length, i.e. the cross-sectional area is at a minimum over a 5mm length instead of at one point. Stress concentrations are also influenced by the method of manufacture of the perforation, i.e. either drilled or punched, which affects the properties of the material surrounding the hole.

Stresses can be more easily redistributed in the direction of load, in the circular and diamond perforated specimens, because the cross-sectional area gradually increases as one moves away from the minimum net cross-section. This is in contrast to tensile specimens with square holes where the stresses can redistribute in the transverse direction but not in the lengthways direction because the minimum net cross-section remains constant. Furthermore, a sudden change in cross-sectional area occurs at either end of the square perforation increasing the severity of the stress concentration. The probability of an inclusion or localised imperfection in the high stress region of the square perforated test specimens is increased compared with the other shape perforations, due to the greater length of the minimum cross-section. Table 4 gives the mean test-to-predicted values for the triplicate tests completed for each sheet steel type and direction.

For almost all G550 sheet steels the specimens with square holes have lower test-to-predicted ratios compared with test specimens which have circular and diamond shape holes. For 042-G550 sheet steel specimens with square and diamond shape holes the tensile predictor equation (Eq. 1) is slightly unconservative, i.e. test-to-predicted ratios are below unity, however the worst case is only 0.979 for diagonal left base metal thickness calculated values. All specimens with circular holes have test-to-predicted tensile ratios which are slightly conservative. Test specimens obtained from the transverse direction do not have markedly lower test-to-predicted ratios, although they exhibit significantly less ductility.

Table 4 5mm Perforated Tensile Test Data Test-To-Predicted Mean Values

Specimen Type	*Direction*	*5mm* ● P_t / P_p	*5mm* ■ P_t / P_p	*5mm* ◆ P_t / P_p
042-G550	*Longitudinal*	1.029	0.981	0.996
	Transverse	1.014	0.984	0.989
	Diagonal Right	1.039	0.990	0.990
	Diagonal Left	1.029	0.979	0.983
060-G550	*Longitudinal*	1.006	1.004	1.026
	Transverse	0.994	1.003	0.992
	Diagonal	1.003	1.003	1.016
060-G300	*Longitudinal*	1.038	1.024	1.001
	Transverse	1.042	1.051	1.028
	Diagonal	1.037	1.040	1.022
NZ 040-G550	*Longitudinal*	1.062	0.989	0.987
NZ 040W-G550	*Longitudinal*	0.987	0.978	1.021
NZ 055-G550	*Longitudinal*	1.022	0.972	0.979
NZ 055W-G550	*Longitudinal*	1.002	0.988	1.017

Note: Material properties were calculated using the base metal thickness.

G550 tensile specimens 0.60mm in thickness produce consistent test-to-predicted tensile ratios for the three types of holes regardless of direction. Specimens tested in the transverse direction have marginally unconservative test-to-predicted ratios for the diamond (0.992) and circular (0.994) shape perforations, but these values are approximately equal to unity.

The 060-G300 perforated tensile specimens reveal that stress concentrations can be easily redistributed for fully annealed thin sheet steels. All test-to-predicted tensile ratios are greater than unity without a bias towards direction, however specimens with diamond shape perforations give test-to-predicted ratios which are slightly less than the circular and square perforated specimens.

The results obtained from the New Zealand sheet steels show an inconsistent pattern concerning the performance of perforated tensile coupon tests. The test-to-predicted tensile ratios for all perforated coupons are near unity, which indicates that no significant unconservative behaviour exists. Coupons with square perforations perform the worst for three of four New Zealand steels, i.e. 040W, 055 and 055W-G550, with base metal thickness test-to-predicted ratios of 0.972 to 0.988. The 040-G550 test specimens with diamond shape holes have a mean test-to-predicted ratio of 0.987, which is slightly lower compared with the square perforated specimens (0.989).

Overall, no dramatic decrease in the test-to-predicted tensile ratio, or ability to predict the ultimate tensile load of the perforated tensile specimens occurs with change in the type of hole or type of manufacture, although specimens with square shape holes perform the worst in most cases. This indicates that the three types of stress concentrations caused by the different hole shapes can be redistributed over the cross-section by thin G550 sheet steels. Furthermore, the net cross-section ultimate tensile strength can be adequately predicted using current design provisions. These results are in line with the Dhalla and Winter *(1974a,b)* type Z steel observations, however, the thinner G550 sheet steel (0.42mm) performs better than the thicker type Z steel (0.965mm).

4.10 Comparison of Perforated Fracture-to-Ultimate Load Ratios

As noted in the discussion of solid test specimens the ratio of fracture-to-ultimate load, P_f / P_t, can be used to indicate the amount of local straining which occurs after the tensile specimen has reached its ultimate load carrying capacity, i.e. the lower the P_f / P_t ratio the greater the degree of ductility. The mean P_f / P_t values listed in Table 3 do not indicate the variation in fracture load with hole type and size, i.e. the stage at which fracture occurs after ultimate load is reached is dependent on the size of the perforation.

For most sheet steel types the thinner grades result in higher fracture-to-ultimate ratios. The highest P_f / P_t ratios occur for the transverse 042-G550 test specimens where the net cross-section fractures immediately after the ultimate load is reached. 060-G550 specimens show an improvement in fracture load where the specimens from the transverse direction behave similar to the specimens from the longitudinal and diagonal directions. In all cases, except for transverse 042-G550 specimens, the sheet steels tested possess adequate ability for fracture to occur well past ultimate.

Perforation type and shape has a large effect on fracture loads, with 5mm square and 1mm circular holes resulting in the highest P_f / P_t values, and 7mm circular holes the lowest P_f / P_t values. Test specimens with square perforations yield the poorest results because the maximum stress in the test coupon extends along a 5mm length rather than at one instantaneous point, as occurs with the diamond and circular shape holes. The 5mm square perforated specimens also have a higher probability of containing imperfections, inclusions and slip planes in the high stress region, which can precipitate final fracture of the specimen. The notch sensitivity of the G550 sheet steels causes specimens with a 5mm diamond shape hole to have either equal or worse P_f / P_t values compared with specimens with a 5mm circular hole (see Rogers and Hancock, *(1996)*).

5 Reliability Study

5.1 General

A reliability study was completed to establish the applicability of current net cross-section ultimate tensile design equations to G550 sheet steels. An AISI Commentary *(1997b)* based calibration method is presented for the Australian / New Zealand *(SA/SNZ, 1996)*, North American *(CSA, 1994; AISI, 1997a)* and European *(Eurocode, 1996)* Design Standards. Data from the perforated test specimen study presented in this paper is supplemented with material information on G550 sheet steels from a BHP G550 Commonisation Study *(1996)*. A relationship between test data from the University of Sydney and BHP Steel was defined through tensile coupon testing completed at BHP Steel, Port Kembla, using sheet steels from the University of Sydney. A ratio of static Sydney ultimate strength to dynamic BHP ultimate strength is made available for use in the reliability study calibration procedure.

5.2 BHP G550 Commonisation Study

Data was obtained from a G550 Commonisation Study *(1996)* completed by BHP Steel Research, Port Kembla, for a wide array of zincalume coated 042-G550 sheet steels. Tensile specimens fabricated from the sheet steels included in this BHP study provide data covering the majority of possible material properties available from various rolling mills. This data is usable because of the comparative study completed with test specimens from the University of Sydney and BHP Steel Research. The material properties for 135 tensile coupons obtained from 15 different coils are included as data for the reliability study. These specimens were milled from three directions in the plane of the sheet, i.e. longitudinal, transverse and diagonal, as was the procedure for specimens tested at the University of Sydney. The average ultimate strength of the BHP Commonisation

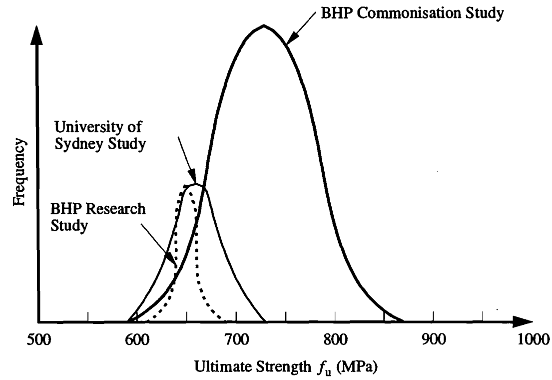

Fig. 4 042-G550 (Longitudinal) Ultimate Strength Distribution

Study sheet steels is a minimum of 69MPa greater than that obtained for the University of Sydney 042-G550 steels. Standard deviations for the test data, which range from 35.6 to 42.1MPa depending on the direction of the material, indicate a large variation in ultimate strength between coils included in the BHP Commonisation study. This is in contrast to the University of Sydney study where all 042-G550 test specimens were obtained from one coil, and the standard deviation of the test data reached a maximum of 14.4MPa for coupons tested in the transverse direction (see Rogers and Hancock *(1996)*). The ultimate strength variation of longitudinal 042-G550 tensile specimens tested for the different studies is shown in Fig. 4.

5.3 AISI Calibrated Resistance, ϕ, Factors

The reliability of a structure at various limit states can be estimated by means of a first and second order moment (FOSM), i.e. mean and coefficient of variation, reliability analysis method. Standards which incorporate a limit states philosophy as a basis for design, e.g. Australia / New Zealand AS/NZS 4600 *(1996)*, are dependent on load, γ_i, and resistance, ϕ, factors to account for uncertainties and variabilities associated with loads, analysis, the limit state model, material properties, geometry and fabrication. Limit states design provides a higher degree of reliability in comparison to allowable stress design because of the ability to account for the variance in different types of loads, e.g. dead and wind, and structural resistance *(AISI, 1997b)*.

Limit states design philosophy requires that the sum of the factored loads applied to a member be less than or equal to the factored resistance of the member, as follows;

$$\sum \gamma_i Q_i \leq \phi R_n \quad (2)$$

where Q_i represents the load effects and R_n represents the nominal resistance. Formulation of limit states design standards involves the definition of reliability indices, β, which depend only on measures of central tendency and dispersion, and are a measure of the safety of a design, i.e. when multiple β values are compared the larger is considered more reliable with a lower probability of failure *(AISI, 1997a; Ellingwood et al., 1980).* The basic equation used to calculate resistance factors, ϕ, based on a reliability index, β, is specified by the AISI Commentary *(1997b)*, as well as by Ravindra and Galambos *(1978).*

$$\beta = \frac{ln(R_m/Q_m)}{\sqrt{V_R^2 + V_Q^2}} \tag{3}$$

Formulation of an equation which can be used to relate the safety index, β, with the resistance factor, ϕ, as given below, is shown in Rogers and Hancock *(1996).*

$$\beta = \frac{ln((M_m \cdot F_m \cdot P_m)/(0.691\phi))}{\sqrt{V_M^2 + V_F^2 + V_P^2 + 0.21^2}} \quad \textit{Australia and Canada} \tag{4}$$

Resistance factors, ϕ, may be calculated for the ultimate tensile strength expression of each design standard by rearranging Eq. 4, substituting an appropriate value for the target reliability index, β_o, and solving for ϕ. The AISI Commentary *(1997b)* recommends that β_o be defined as 2.5 for structural members, whereas the Canadian Commentary *(CSA, 1995)* recommends that β_o range between 3.0 and 4.0 (β_o = 4.0 is applicable to normal buildings where sudden failure may occur *(CSA, 1981)*). A β_o of 3.0 was assumed for calibration of the European Standard *(Eurocode, 1996)* following the AISI Commentary specified procedure.

Table 5 042-G550 Resistance Factors, ϕ, for Net Cross-Section Tensile Resistance in Fracture

Standard		*Longitudinal*	*Transverse*	*Diagonal*[a]
Australia	β_o	2.5/3.2	2.5/3.2	2.5/3.2
(SA/SNZ, 1996)	ϕ *(calculated)*	1.07/0.92	1.20/1.03	1.05/0.90
	$0.85\phi_t$ *(current)*	0.77	0.77	0.77
New Zealand	β_o	2.5/3.2	2.5/3.2	2.5/3.2
(SA/SNZ, 1996)	ϕ *(calculated)*	1.13/0.97	1.27/1.09	1.10/0.94
	$0.85\phi_t$ *(current)*	0.77	0.77	0.77
Canada	β_o	3.0/3.2/4.0	3.0/3.2/4.0	3.0/3.2/4.0
(CSA, 1994)	ϕ *(calculated)*	0.96/0.92/0.77	1.08/1.03/0.87	0.94/0.90/0.75
	ϕ_u *(current)*	0.75	0.75	0.75
USA	β_o	2.5/3.2	2.5/3.2	2.5/3.2
(AISI, 1997a)	ϕ *(calculated)*	1.13/0.97	1.27/1.09	1.10/0.94
	ϕ_t *(current)*	0.75	0.75	0.75
Europe	β_o	3.0/3.2	3.0/3.2	3.0/3.2
(Eurocode, 1996)	ϕ *(calculated)*	0.97/0.93	1.09/1.05	0.95/0.91
	$1/\gamma_{M2}$ *(current)*	0.80	0.80	0.80

[a]Diagonal right and left test specimens have been combined into the diagonal direction.

However, the target reliability index used to calibrate the current tensile resistance equations given in the AISI Specification *(1997a)*, β_o = 2.5 *(Ellingwood et al., 1980)*, was based on failure by yielding of the net cross-section. The current tensile equation specified in the design standards considered for this report is a function of the ultimate strength of the net cross-section, hence, failure is by fracture of the specimen rather than yielding. This characteristic was accounted for in calibration of the AISC *(1986)* tensile equations, where separate target reliability indices were used for yielding and fracture. Ellingwood *et al. (1980)* recommend that for hot rolled sections with a dead to live load ratio of 0.20 target reliability indices of 2.5 and 3.2 be used for yielding and fracture, respectively.

Results of the reliability study following the AISI Commentary *(1997b)* recommended calibration procedure reveal that the calculated resistance factors exceed the requirements currently specified in the Australian / New Zealand *(SA/SNZ, 1996)*, North *American (CSA, 1994; AISI, 1997a)*, and European *(Eurocode, 1996)* Design Standards. Table 5 lists the current and calculated resistance factors in the longitudinal, transverse and diagonal directions for various target reliability indices. The calculated resistance factors are greater than the current specified values for all design standards considered, which indicates that the load carrying capacity of G550 tensile perforated tensile specimens can be adequately predicted using existing procedures. See Rogers and Hancock *(1996)* for all pertinent statistical parameters necessary for the calculation of resistance factors.

6 CONCLUSIONS

Test results indicate that the ability of G550 sheet steels to undergo deformation is dependent on the direction of load within the material, with the transverse specimens exhibiting the least amount of overall, local and uniform elongation. The G550 sheet steels do not meet the Dhalla and Winter material requirements regardless of direction, except for uniform elongation in longitudinal test specimens. The three types of stress concentrations caused by the different shape perforations can be redistributed over the cross-section by thin G550 sheet steels. Furthermore, the net cross-section ultimate tensile strength can be adequately predicted using current design provisions. Perforation type and shape has a large effect on fracture loads, with square and 1mm circular holes resulting in the highest fracture-to-ultimate values, and 7mm circular holes the lowest P_f / P_t values, where low values are preferred. All solid tensile test specimens, except for transverse 042-G550 coupons, exhibit fracture-to-ultimate load ratios within a range that shows acceptable levels of deformation prior to final fracture. Results of the reliability study following the AISI Commentary recommended calibration procedures reveal that the calculated resistance factors exceed the requirements currently specified in the Australian / New Zealand, North American, and European Design Standards. The load carrying capacity of G550 concentrically perforated tensile specimens can be adequately predicted using existing limit states design procedures. The G550 sheet steels have properties similar to the Dhalla and Winter type Z steel, which fully plastified for perforated longitudinal specimens and achieved 94% of the net tensile capacity for perforated transverse specimens. The tested steels out-performed the Dhalla and Winter steels, which indicates that a reduction to 75% of the specified material properties appears conservative for design purposes.

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