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Sub-zero temperature mechanical properties of cold-rolled steel sheets

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Abstract: Cold-formed steels are replacing conventional building materials in many building applications due to the many benefits including lightweight and low cost of construction. Recent research has focused on the fire resistance of cold-formed steel (CFS) construction at material and member levels and advanced the knowledge of their fire performance significantly. However, the performance of CFS members at sub-zero temperatures has not been investigated. Although several studies have been conducted on the mechanical properties of other types of steel at sub-zero temperatures, no studies have been conducted on sub-zero temperature mechanical properties of thin cold-formed steels. In this research, low and high strength cold-rolled steel sheets were tested in the temperature range of 20 to -70 °C to determine their sub-zero temperature mechanical properties. Predictive equations are proposed for yield strength, Young's modulus, upper yield strength, ultimate strength and stress at 2% total strain using the experimental results. Finally, suitable stress-strain models are recommended for the prediction of sub-zero temperature stress-strain curves and their use in numerical studies.

Keywords: Cold-rolled steel sheets; Cold-formed steel sections; Mechanical properties; Sub-zero temperatures; Two-stage stress-strain model.

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1. Introduction

The polar regions and high altitude mountains experience harsh cold climatic conditions. Latip et al. [1] reported that -87.2 °C (Vostok Station in East Antarctica) was the lowest recorded temperature on the earth. It was recorded in the South Pole while -68 °C was the lowest temperature recorded in the Arctic region (the North Pole). People have been living in the Arctic Circle, which includes part of Russia, United-states, Canada, Norway and Greenland, for thousands of years despite the sub-zero temperature environment. Although Antarctica does not contain permanent habitats, many researchers and tourists visit the South Pole. On the other hand, North and South poles are rich in natural resources. Increased oil and gas explorations in North Pole have attracted more people to move closer to the region. However, people living in the polar regions or high altitude mountains do not have similar infrastructure facilities enjoyed by others due to the difficulties in using conventional building materials such as hot-rolled steel and concrete. Shorter day time, transportation difficulties, freezing temperatures, and knowledge gaps on the performance and design of building materials at sub-zero temperatures are some of the construction difficulties in the polar regions.

Although timber is one of the popular materials in the polar regions, it is heavier, less durable and vulnerable in fire compared to cold-formed steel (CFS). Pre-assembled Light Gauge Steel Frame (LSF) wall and floor systems made of cold-formed steel members are suitable for cold-region construction as they reduce the construction and transportation costs. Also, the knowledge enhancement in cold-formed steel design and construction at ambient and elevated temperatures in recent decades is an added advantage. However, limited effort has been taken in investigating the behaviour of cold-formed steel members at sub-zero temperatures so far. This means that although cold-formed steel construction is now widely used in residential, commercial and industrial buildings all over the world, it may not be used in the buildings constructed in cold-regions. Polyzois et al. [2] investigated the compression capacity of cold-formed steel angles used in lattice towers in the temperature range of -45 to 25 °C. Abdel-Rahim and Polyzois [3] investigated the mechanical properties of cold-formed steel sections, which are also used in lattice towers, in the range of ambient temperature to -50 °C. They concluded that low temperatures significantly affect the yield strength, ultimate strength and maximum percentage of elongation of steels. However, the thickness of their sections is higher compared to those used in LSF walls and floors. To date, there are no studies on the sub-zero temperature mechanical properties of cold-rolled steel sheets or cold-formed steel members.

On the other hand, many researchers have investigated the sub-zero temperature mechanical properties of other metals. Rosenberg [4] investigated the low-temperature mechanical properties of aircraft metals. Levings and Sritharan [5], Yan et al. [6], Yan and Xie [7] and Azhari et al. [8] investigated the sub-zero temperature mechanical properties of ASTM A706 Grade 420 steel reinforcement, normal and high strength hot-rolled steel, various grades of reinforcement steel and ultrahigh strength steel, respectively. Levings and Sritharan [5] showed that ASTM A706 Grade 420 steel reinforcement experienced 5.1% and 6.3% increment in yield and ultimate strengths, respectively at -40 °C. Similarly, Yan et al. [6] reported that yield strength, Young's modulus, ultimate strength and fracture strain increased as the temperature reduced. They observed yield strength increments of 13%, 21% and 7% at -80 °C for 4 mm mild steel, 12 mm mild steel and high strength steel, respectively. However, Yan and Xie [7] found that ductility of reinforcement steel reduced as temperature decreased while yield and ultimate strengths increased. Azhari et al. [8] also found that yield and ultimate strengths of ultra-high strength steel increased with reducing temperatures below zero while ductility reduced. Hence, it is important that sub-zero temperature mechanical properties of cold-rolled steels are also investigated to understand the variations of mechanical properties as a function of reducing temperature to sub-zero levels.

An experimental study was therefore undertaken to investigate the sub-zero temperature mechanical properties of cold-rolled steel sheets, such as yield strength, upper yield strength, ultimate strength, stress at 2% total strain, Young's modulus, ultimate strain and fracture strain. Using the experimental results, new equations were proposed to predict the sub-zero temperature mechanical properties of cold-rolled steel sheets. Suitable stress-strain models were also developed for cold-rolled steel sheets exposed to sub-zero temperatures. This paper presents the details of this experimental study and its results.

2. Experimental study

2.1. Test coupon and test method

A series of uniaxial tensile tests was conducted to determine the sub-zero temperature mechanical properties of low (G300) and high (G550) strength cold-rolled steel sheets. The base metal thicknesses of chosen steels are 0.55 mm, 0.80 mm and 1.0 mm for G300 steels and 0.55 mm, 0.75 mm and 0.95 mm for G550 steels. Kankanamge and Mahendran [9] and Rokilan and Mahendran [10] showed that high strength steel (HSS) grades such as G450, G500 and

G550 exhibit similar yield strength reduction at elevated temperatures, while Rokilan and Mahendran [10] showed that low strength steel (LSS) grades such as G250 and G300 exhibit similar yield strength reduction at elevated temperatures. Hence, G300 and G550 steels were selected in this experimental study to represent low strength and high strength cold-rolled steel sheets, respectively.

Tensile coupons were extracted in the longitudinal direction of cold-rolled steel sheets and prepared as per the dimensions given in AS 1391 [11] (Fig. 1). The ambient temperature tensile testing standard of metals was used since there is no Australian Standard for sub-zero temperature tensile testing of metals. However, the dimensions were verified using the Internationl Standard for sub-zero temperature tensile tests of metals, BS EN ISO 6892-3 [12].

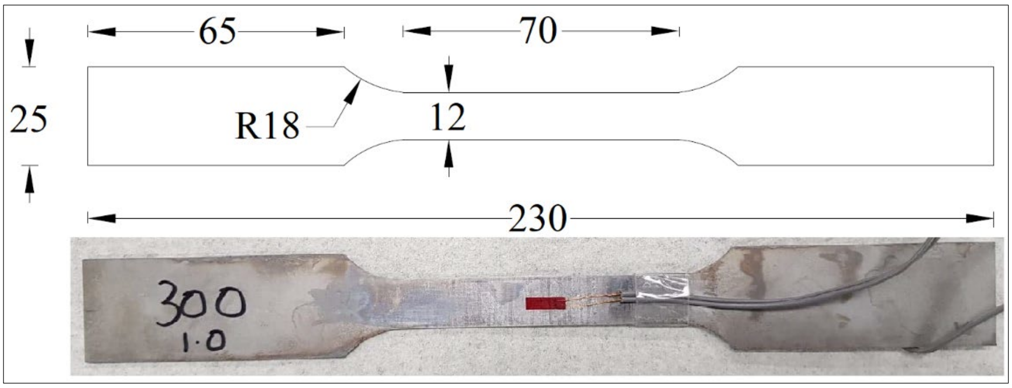


Fig. 1. Dimensions of tensile coupons

Tensile coupons were extracted using the water jet cutting method as recommended by Imran et al. [13]. The extracted coupons were then subjected to a chemical etching process to remove the corrosion prevention coating and kept inside dilute HCL until the coating was removed completely. Finally, they were washed using distilled water followed by acetone. The base metal thickness and the width of the coupons were measured at three locations within the gauge length using a Vernier calliper. Average measured values of base metal thickness and width were used in the mechanical property calculations. Five mm strain gauges with an operating temperature range of -196 to 150 °C were attached to both sides of the chemically etched coupons using Cyanoacrylate adhesive and cured for 24 hours at room temperature. The surface of the chemical etched coupon was cleaned by acetone, acidic surface cleaner and a neutralizer before attaching the strain gauges as impurities on the coupon surface affect the functionality of strain gauges. Fig.1 shows a coupon with strain gauges attached. Attaching two strain gauges helped to ensure the in-plane verticality of the tensile coupon while the coupon width at the ends was selected as the same as that of the grip to ensure the coupon's out of plane verticality. Both strain gauges showed similar strain readings as the level of initial bending residual stress is negligible in cold-rolled steel sheets.

The maximum sub-zero temperature selected in this study was -70 °C since the maximum measured temperature in the arctic region, where people live, is -68 °C. Also, the temperature of steel members will be less than the outside temperature as they are protected by boards and insulation materials. The tensile coupons were tested at 20 °C, -10 °C, -30 °C, -50 °C and -70 °C under steady-state conditions. It is not possible to use transient state test method, one of the testing methods used in elevated temperature coupon tests, since the yield strength of steel is likely to increase with reducing temperature. Two tensile coupons were tested for each temperature and the third test was conducted if individual results deviate from the mean by more than 5%. Tensile tests were not conducted at a temperature between ambient temperature and -10 °C since the differences in mechanical properties between these two temperatures were small.

2.2. Test set-up and procedure

The sub-zero temperature tensile coupon test facility at the Queensland University of technology was used to test the coupons at both ambient and sub-zero temperatures. Fig. 2 shows the sub-zero temperature tensile test set-up. It consisted of a 30 kN Instron testing machine, an environmental chamber with a Eurotherm control unit and a liquid nitrogen cylinder. Liquid nitrogen was used as the cryogen in this study as it is the best cryogen compared with other cryogens such as carbon dioxide, ethanol and dry ice. The environmental chamber has an operating temperature range of -100 °C to 350 °C. The Instron testing machine was connected to a Bluehill universal software system for data acquisition purposes and to control the loading process. A laptop with LabVIEW 2017 software was used to record the measured strains from the strain gauges and temperatures from the thermocouples attached to the tensile coupons.

Thermocouples were also attached to the tensile coupon, which was then held between the top and bottom grips of the Instron testing machine (Fig. 3). Lead wires of strain gauges and thermocouples were taken out through the insulated orifice in the environmental chamber and connected to the data logger. After the initial set-up, the tensile coupon was loaded to 50% of the expected yield load using a displacement control method (1mm/min) [10,13] and then unloaded. These loading and unloading processes were repeated three times for each coupon.

The Young's modulus was calculated for each loading process and compared with the nominal value of 200 GPa. This procedure was used to ensure the vertical and horizontal alignments of the coupon. Neuenschwander et al. [14] also used a similar approach in their investigation. The sub-zero temperature Young's modulus increment factors were calculated using the ambient temperature Young's modulus obtained from the preloading process and the corresponding sub-zero temperature Young's modulus as recommended in [13].

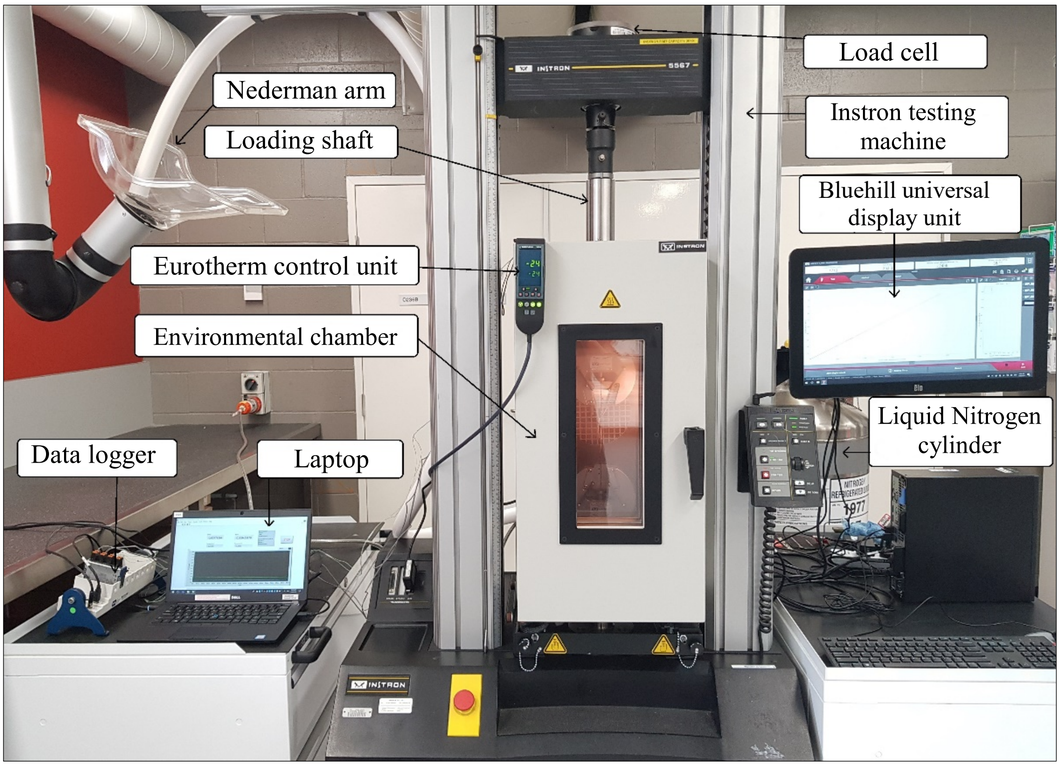


Fig. 2. Sub-zero and ambient temperature tensile test set-up

After the initial set-up, the target temperature of the environmental chamber was set using the Eurotherm control unit. The target temperature was set lower than the test temperature as there was a temperature difference between the in-built thermocouple attached to the environmental chamber wall and the thermocouples attached to the tensile coupon due to heat loss. Liquid nitrogen was then released into the chamber and distributed evenly through a fan attached to the chamber. The target temperature was adjusted based on the readings of the thermocouples attached to the coupon. The tensile coupon was subject to contraction as the coupon temperature decreased. The tensile load created by the contraction of the tensile coupon was released and maintained at 100-150 N throughout the cooling process. The coupon was kept at the target test temperature for about 15 min to ensure a uniform temperature across the cross-section. Finally, the applied tensile load was increased using a displacement control method (1 mm/min) until the coupon failed. The corresponding strain rate is 0.000238/s, which falls within the AS 1391 [11] recommended range of 0.0002 to 0.0008/s. Although the strain rate can affect the measured mechanical properties of CFS, its effect on the increment factors are less than that on the mechanical properties.

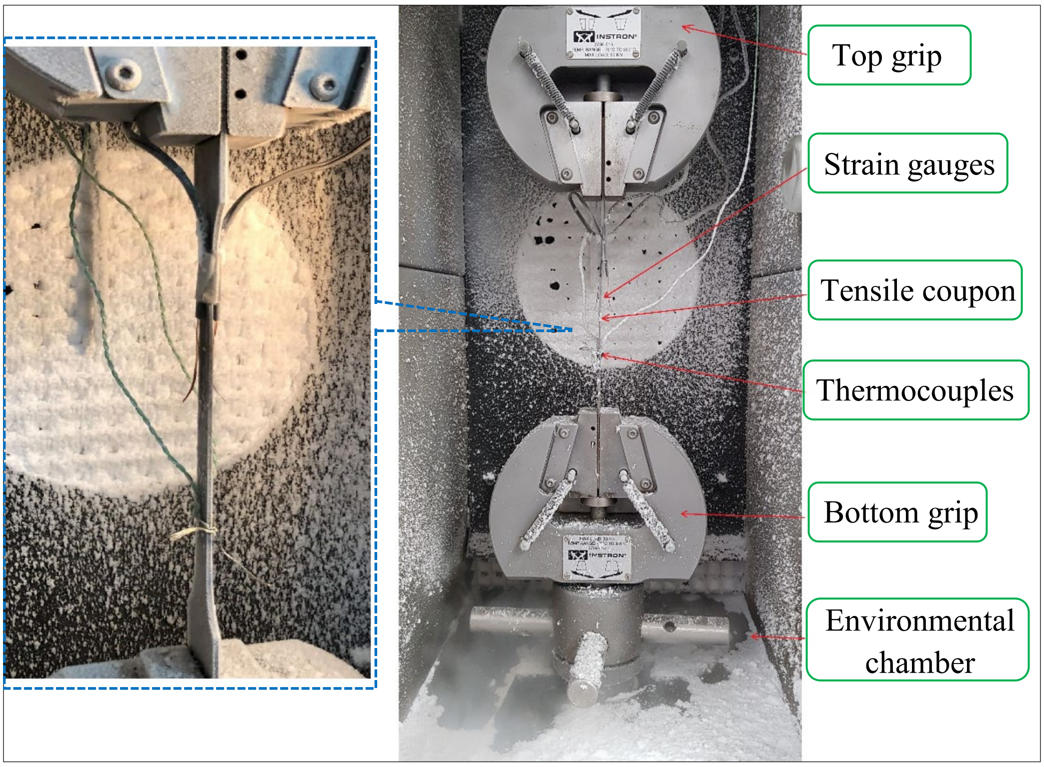
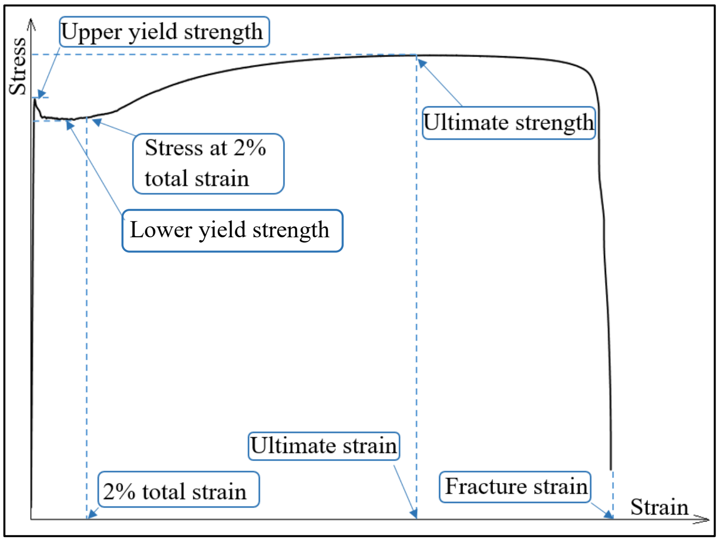


Fig. 3. Arrangement of strain gauges and thermocouples

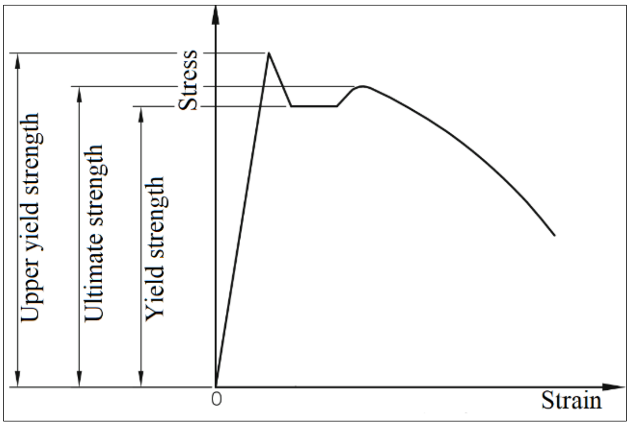
3. Sub-zero and ambient temperature mechanical properties

This section presents the measured sub-zero temperature mechanical properties of six different cold-rolled steel sheets (LSS G300 and HSS G550 steels with three thicknesses each) including their full engineering stress-strain curves based on the original tensile coupon dimensions (Figs. 5 and 6). The ambient and sub-zero temperature mechanical properties such as yield strength (0.2% proof stress if the stress-strain curve exhibits gradual yielding), upper yield strength, stress at 2% total strain, Young's modulus, ultimate strength, ultimate strain and fracture strain were determined from the experimental stress-strain curves. The term yield strength is used in this paper instead of lower yield strength and 0.2% proof stress as AS/NZS 4600 [15] recognises them as the yield strength. The average mechanical properties were obtained from at least two coupon tests for ambient and sub-zero temperatures. These results showed that mechanical properties in general increased/improved with decreasing temperature. The average mechanical properties of cold-rolled steel sheets were then used to derive the predictive equations of sub-zero temperature mechanical property increment factors.

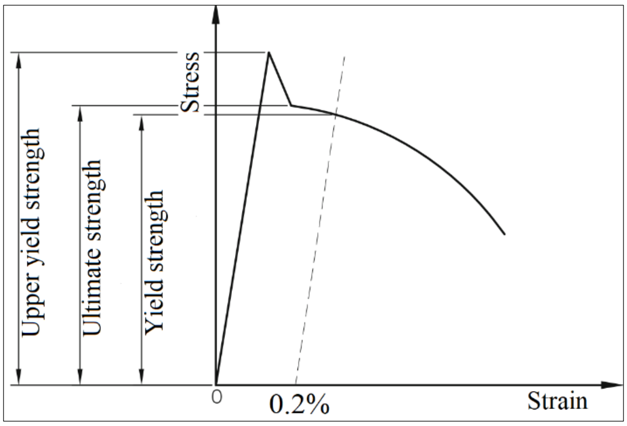
The stress-strain curves of 0.95 mm G550 steel up to -50 °C, 1.0 mm G300 steel at -10 °C and all the G300 cold-rolled steel sheets at ambient temperature show that the ultimate strength is higher than the upper yield strength. Hence, the mechanical properties in these cases were obtained as per Fig. 4 (a), while 0.2% proof stress was used as the yield strength for 0.95 mm G550 steel at ambient temperature and -10 °C, which exhibited gradual yielding. However, the upper yield strength is higher than the ultimate strength in many other cases, in which case, the upper yield and ultimate strengths were obtained as per the guidance provided in AS 1391 [11] and BS EN ISO 6892-1 [16], (Fig. 4 (b)) while other mechanical properties were obtained as per Fig. 4 (a). The stress-strain curves of 0.55 mm G550 at all the temperatures, 0.75 mm G550 and all the tested G300 at -70 °C do not have either a yield plateau or strain hardening and thus do not match either Fig. 4 (a) or (b). In these cases, the upper yield and ultimate strengths were obtained as per the guidance provided in AS 1391 [11] (Fig. 4 (c)), while other mechanical properties were obtained as per Fig. 4 (a). BS EN ISO 6892-1 [16] does not define the ultimate strength in this case and states that a separate agreement can be made with the parties concerned, if necessary. Also, ASTM A360-19 [17] does not provide a method to determine the mechanical properties in the cases similar to Fig. 4 (b) or (c). However, the reduction rate of stress beyond upper yield strength is significantly less for 0.55 mm G550 in the temperature range of ambient temperature to -50 °C.



a. Stress-strain curve with ultimate strength greater than upper yield strength



b. Stress-strain curve with ultimate strength less than upper yield strength



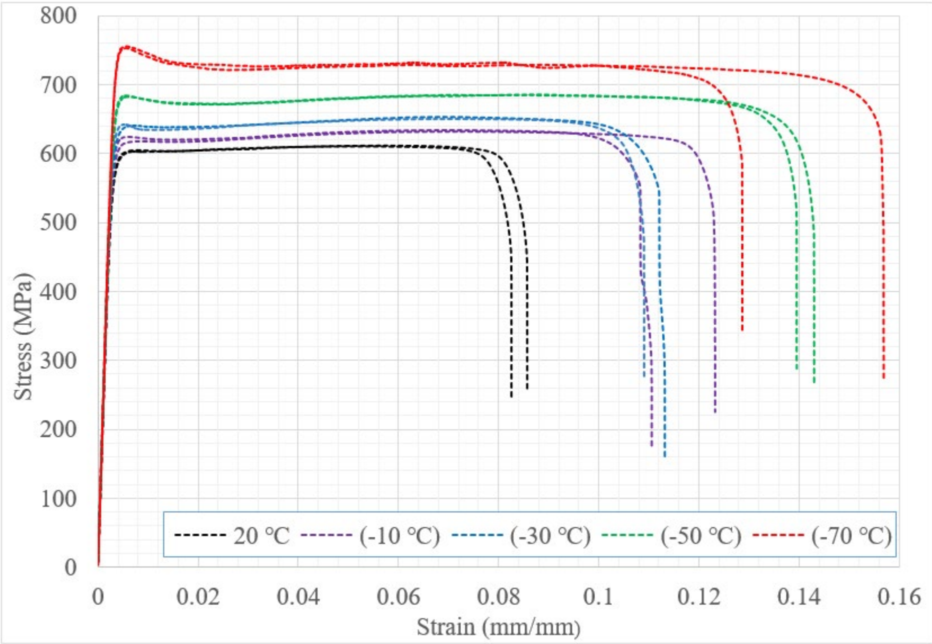
c. Stress-strain curve with ultimate strength less than upper yield strength, but without yield plateau or strain hardening

Fig. 4. Definitions of mechanical properties

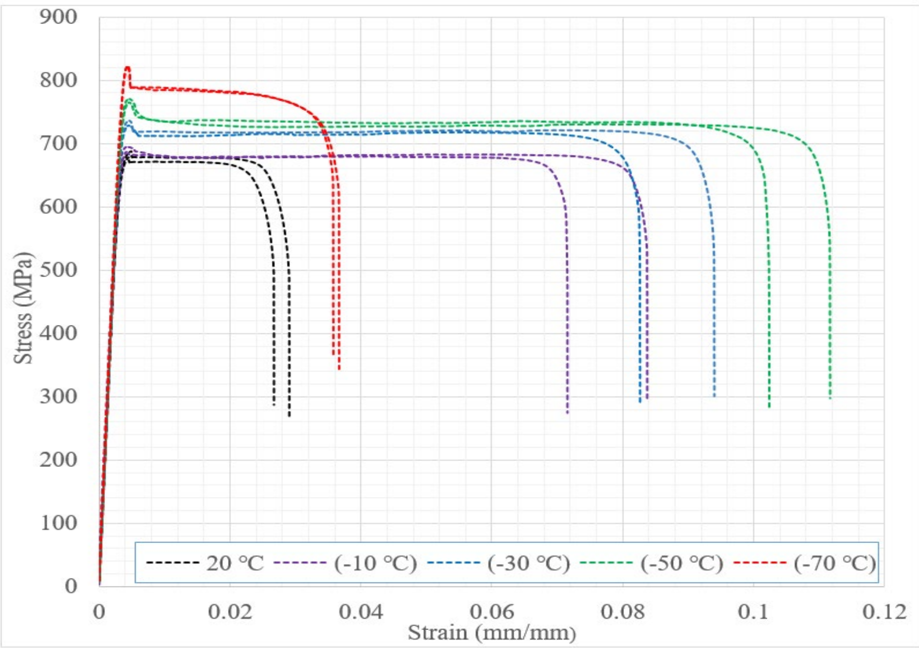
3.1. Stress-strain curves

The engineering stress-strain curves in Fig. 5 and 6 are based on the data obtained from strain gauges, load cell and Instron head movement. Average strains calculated from the two strain gauges attached to both sides of the coupon were used up to the yield strength. However, modified strains based on Equation 1 were used beyond the yield strength. Strain gauges could not be used until the fracture point since they were detached from the coupon due to the large elongation of coupon. This behaviour was observed in many low strength steels (LSS G300) and 0.95 mm high strength steel (HSS G550) tensile coupons. The detachment occurred at a point between yield and fracture strains. On the other hand, strain gauges attached to the 0.55 mm and 0.75 mm G550 remained attached to the tensile coupons due to low fracture strains. Also, the fracture location was away from the centre of the tensile coupon, where strain gauges were attached. However, in this situation, modified strain from Instron head movement gave more realistic results beyond yield strain than the average strain gauge reading as the localised elongation occurred away from the strain gauge locations.

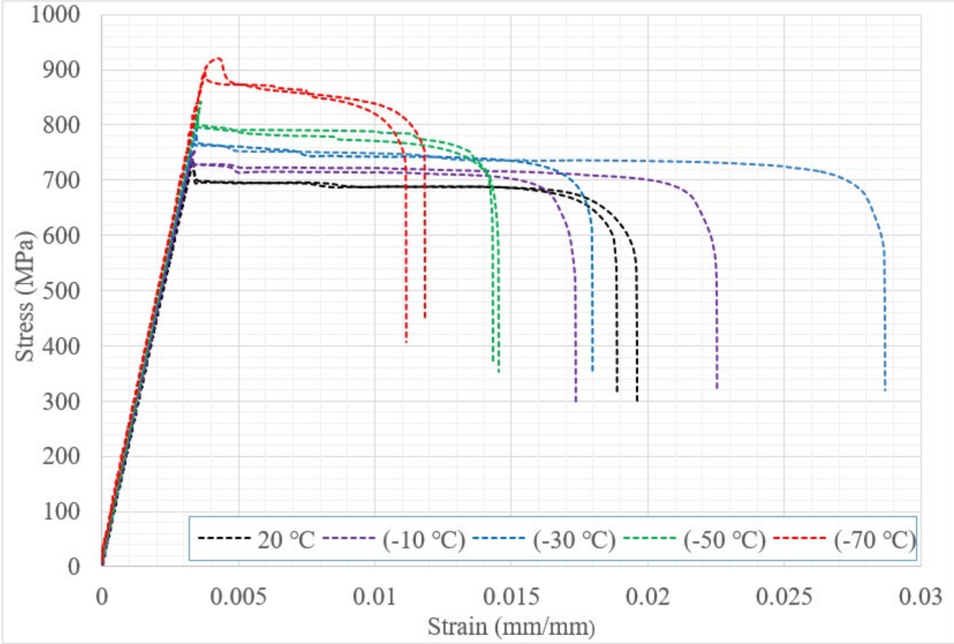
$$\text{Modified strain} = \text{Strain at yield strength from strain gauge measurement} + (\text{Strain from Instron} - \text{Strain from Instron at yield strength}) \quad (1)$$



a. G550 - 0.95 mm

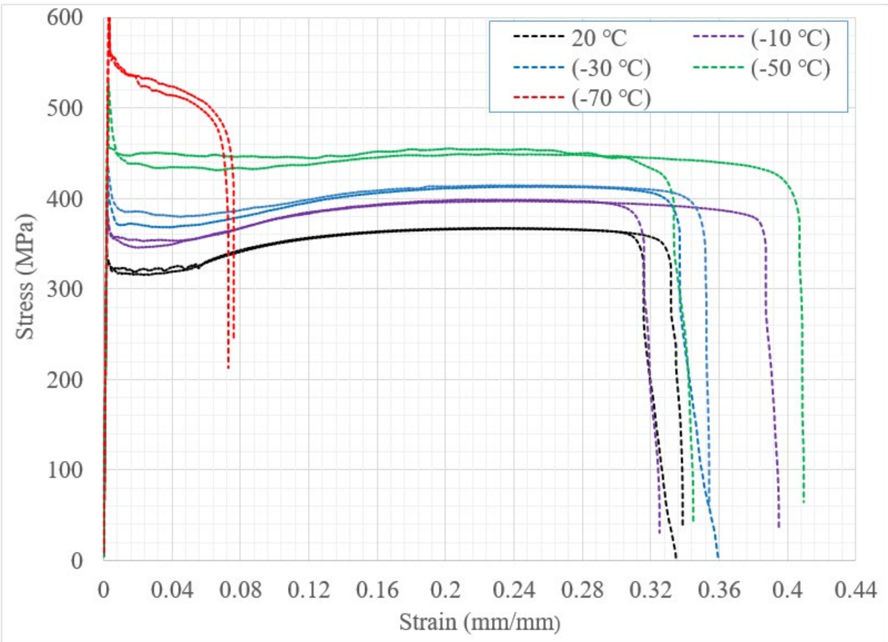


b. G550 - 0.75 mm

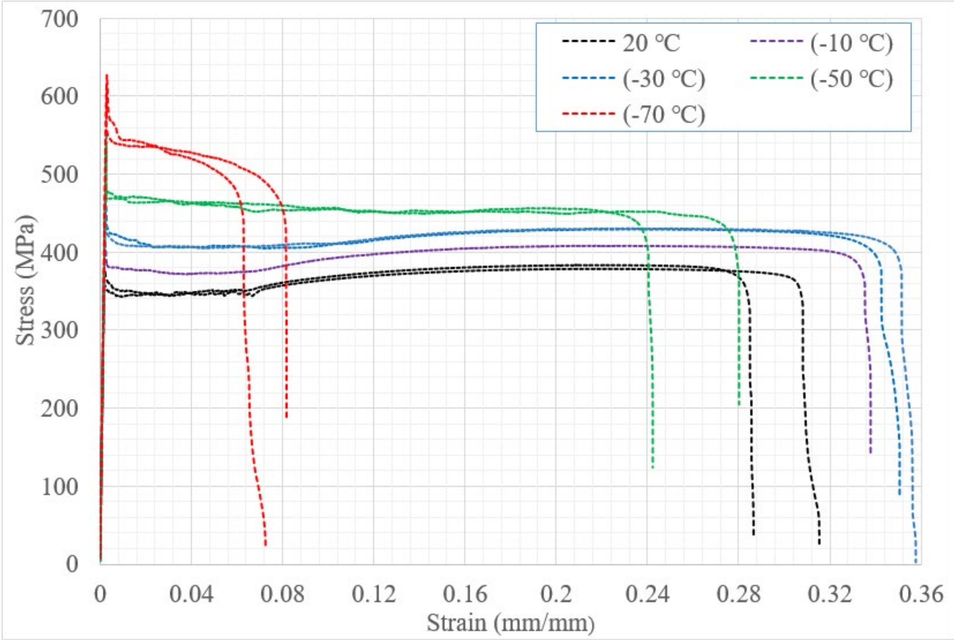


c. G550 - 0.55 mm

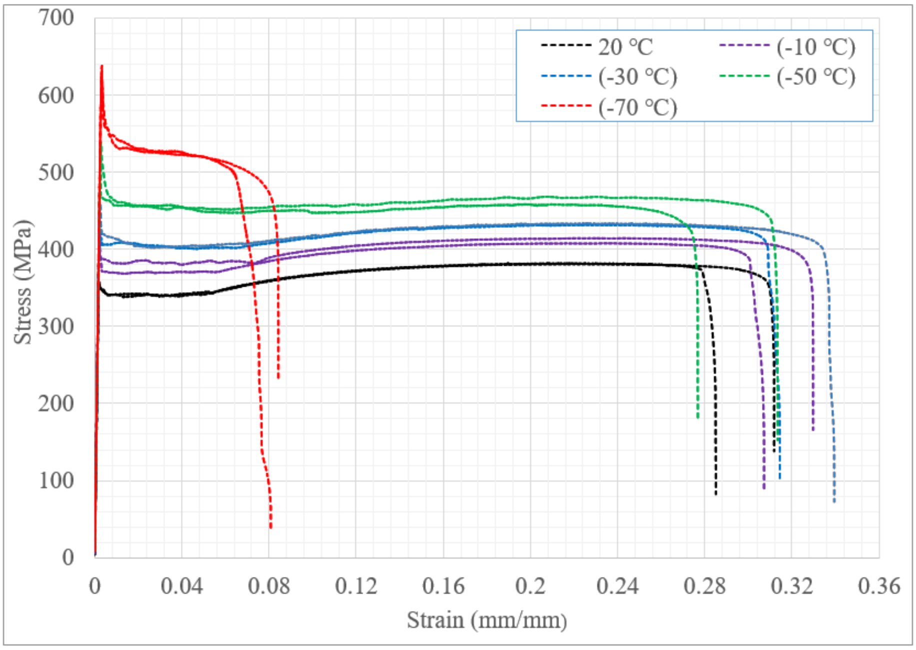
Fig. 5. Experimental stress-strain curves of high strength steels (HSS)



a. G300 – 1.0 mm



b. G300 – 0.80 mm



c. G300 – 0.55 mm

Fig. 6. Experimental stress-strain curves of low strength steels (LSS)

3.2. Yield strength

Yield strength, one of the important mechanical properties used in cold-formed steel design standards, increased as the test temperature decreased (Fig. 7), similar to hot-rolled structural steel and reinforcement steel [5-8]. Also, the rate of increment of both G300 LSS and G550 HSS rises as the temperature drops. It is interesting to note that elevated temperature yield strength reduction factor of LSS is less than that of HSS up to 500 °C [10] while sub-zero temperature increment factor of LSS is higher than HSS. Cold-rolled steels may exhibit this behaviour due to the different levels of cold working applied to LSS and HSS. Fig. 7 shows the increment of 0.55 mm HSS to be 25% while it is 75% for 1.0 mm at -70 °C.

Gradual yielding was observed only for 0.95 mm HSS at ambient temperature and -10 °C whereas sharp yielding was observed in all other cases. However, 0.2% proof stress was used as yield strength for both LSS and HSS at -70 °C (other than 0.95 mm HSS) and 0.55 mm HSS at ambient to -50 °C as the stress-strain behaviour was similar to Fig. 4 (c). Fig. 7 shows the sub-zero temperature yield strength increment factors of LSS and HSS, which are the ratios between sub-zero and ambient temperature yield strengths (Table 1).

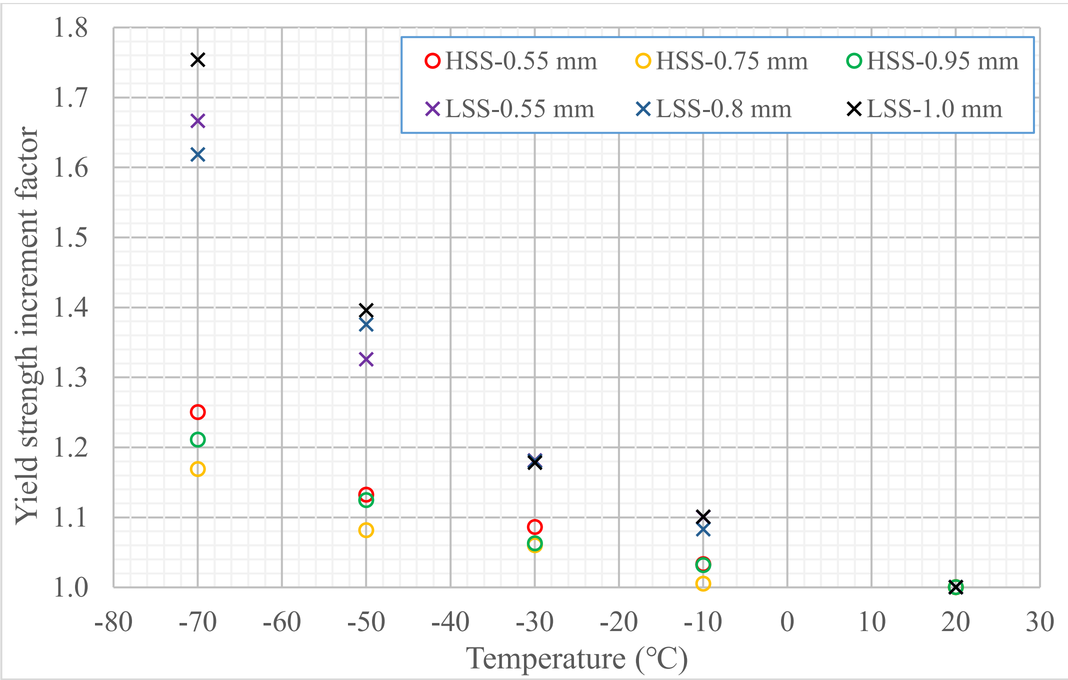


Fig. 7. Yield strength increment factors of cold-rolled steel sheets

Table 1: Yield strengths at ambient and sub-zero temperatures in MPa

Temperature (°C)	High strength steel (G550)			Low strength steel (G300)		
	0.55 mm	0.75 mm	0.95 mm	0.55 mm	0.80 mm	1.0 mm
20	695	674	598	339	344	317
-10	718	678	617	373	372	349
-30	755	715	635	401	406	374
-50	787	729	672	450	473	443
-70	869	788	724	565	556	556

3.3. Upper yield strength

Upper yield strength is not used in the CFS design standard AS/NZS 4600 [15]. However, it is worth discussing upper yield strength under sub-zero temperature mechanical properties as the ratio between upper yield strength to yield strength increases with decreasing temperature. Yield strength of 0.95 mm HSS was taken as the upper yield strength at ambient temperature and -10 °C as 0.95 mm HSS exhibited gradual yielding at these temperatures. LSS exhibits considerable sharp yielding at ambient temperature while HSS exhibits gradual or less sharp yielding. However, the sharp yielding behaviour of both LSS and HSS increases as the temperature decreases. The upper yield strength increment factors (Fig. 8) show the same trend as the yield strength increment factors (Fig. 7). Ambient and sub-zero temperature upper yield strengths are given in Table 2.

Table 2: Upper yield strengths at ambient and sub-zero temperatures in MPa

Temperature (°C)	High strength steel (G550)			Low strength steel (G300)		
	0.55 mm	0.75 mm	0.95 mm	0.55 mm	0.80 mm	1.0 mm
20	727	683	598	357	370	338
-10	752	691	617	418	426	386
-30	790	733	641	457	470	427
-50	833	768	684	535	542	526
-70	908	822	755	634	623	627

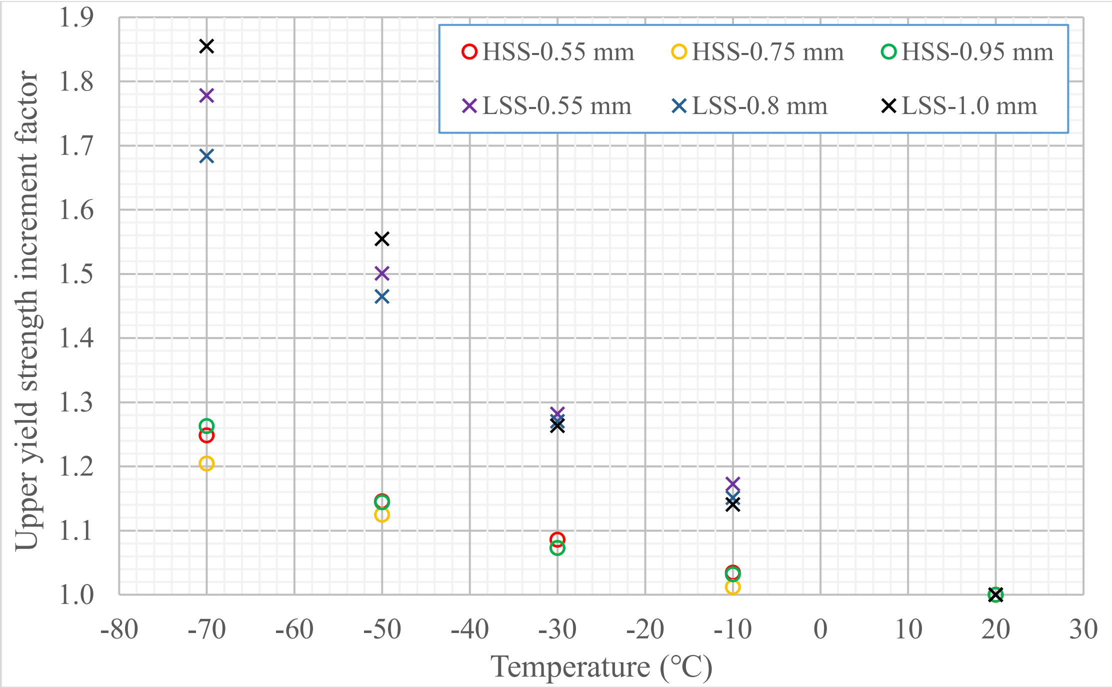


Fig. 8. Upper yield strength increment factors of cold-rolled steel sheets

3.4. Young's modulus

AS/NZS 4600 [15] gives the same elevated temperature Young's modulus reduction factor predictive equation for both LSS and HSS although it gives separate reduction factor predictive equations for yield strength. Similarly, there is a considerable deviation between sub-zero temperature yield strength increment factors of LSS and HSS while Young's modulus increment factors do not show much deviation with steel grade. The maximum increment for Young's modulus is only about 8% while yield strength increases by 75% and 25% for LSS and HSS, respectively. In contrast, Young's modulus reduces considerably with increasing temperature [10].

Young's moduli were obtained from the average strain gauge measurements. Stresses and strains within the 20-50% yield strength range were used to calculate the ambient and sub-zero temperature Young's moduli (Table 3) as recommended in [10]. Sub-zero temperature Young's modulus increment factors given in Fig. 9 are the average ratios between the sub-zero and ambient temperature Young's modulus values of the same coupon.

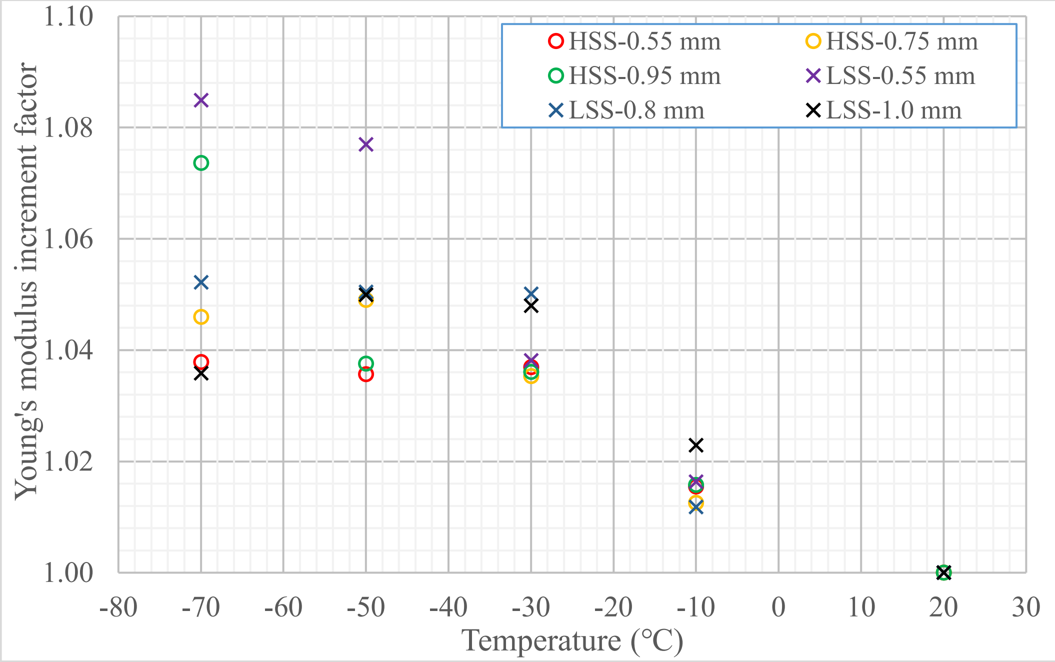


Fig. 9. Young's modulus increment factors of cold-rolled steel sheets

Table 3: Young's modulus at ambient and sub-zero temperatures in MPa

Temperature (°C)	High strength steel (G550)			Low strength steel (G300)		
	0.55 mm	0.75 mm	0.95 mm	0.55 mm	0.80 mm	1.0 mm
20	222054	217914	213958	200576	204179	201027
-10	225871	219571	219896	203981	205248	207443
-30	231073	228119	223416	209697	214343	211215
-50	231449	228216	226416	216742	213483	214290
-70	230190	227499	233108	218713	215442	209800

3.5. Ultimate strength

Ultimate strengths, given in Table 4, were taken as the maximum stress point after the yield plateau for sharp yielding cases and as the maximum stress for gradual yielding cases while Fig. 4 (c) was used to determine the ultimate strength of LSS and HSS at -70 °C (other than 0.95 mm HSS) and 0.55 mm HSS at ambient temperature to -50 °C. The ultimate strength increment factors (Fig. 10) exhibit the same trend as the yield strength increment factors (Fig. 7). However, the rate of increment of LSS is considerably less compared to its yield strength increment rate. This indicates that the ultimate strength to yield strength ratio of LSS drops as the temperature reduces, ie, strain hardening of LSS after the yield plateau reduces as the temperature declines. It is interesting to note that the yield plateau of LSS increases as the temperature reduces (Fig. 6). On the other hand, the rates of increments of yield and ultimate strengths of HSS do not show significant variation.

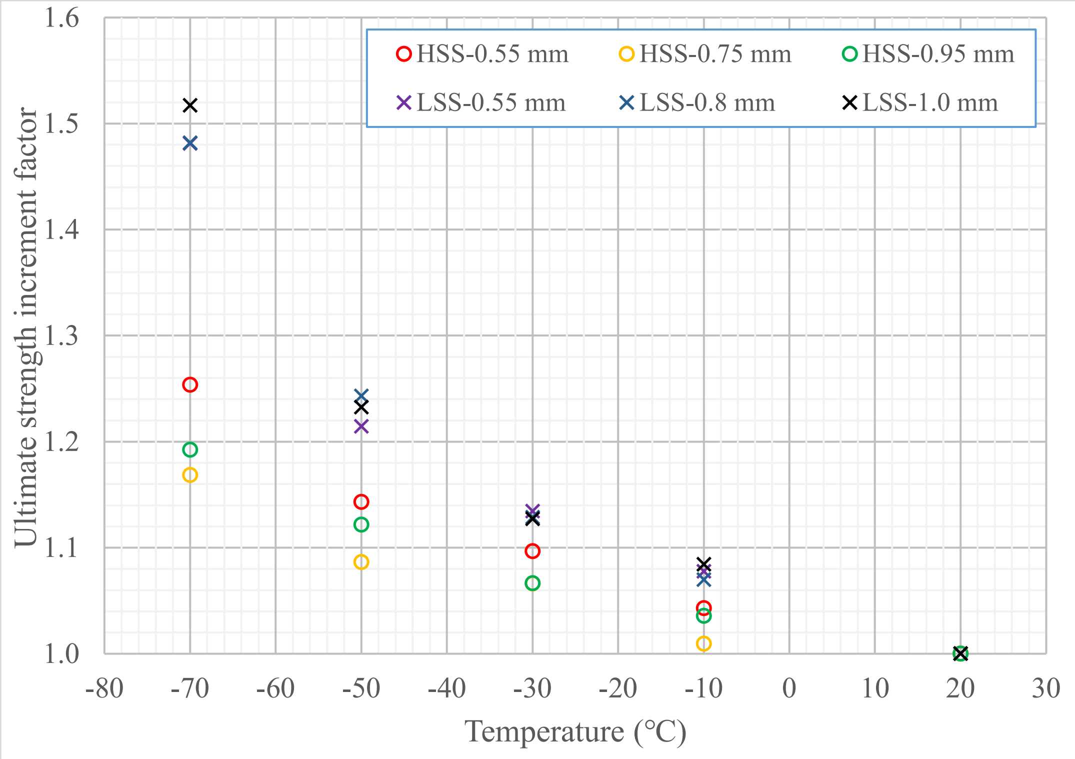


Fig. 10. Ultimate strength increment factors of cold-rolled steel sheets

Table 4: Ultimate strengths at ambient and sub-zero temperatures in MPa

Temperature (°C)	High strength steel (G550)			Low strength steel (G300)		
	0.55 mm	0.75 mm	0.95 mm	0.55 mm	0.80 mm	1.0 mm
20	698	675	611	381	381	367
-10	728	681	633	411	408	398
-30	766	720	652	433	430	414
-50	798	733	686	463	474	452
-70	875	789	729	565	565	557

3.6. Stress at 2% total strain

It is worth to determine and report the stress at 2% total strain, proportional limit stress and 0.05% proof stress when the tensile tests are conducted for research purposes. However, proportional limit stress and 0.05% proof stress are not reported in this paper as most of the tested coupons exhibited sharp yielding. Hence, the proportional limit stress and 0.05% proof stress coincide with the yield strength or are very close to it. Stress at 2% total strain of 0.55 mm HSS is not reported as the tensile coupons failed before they reach the 2% total strain. The increment factors of stress at 2% total strain (Fig. 11) also follow the same trend of yield strength increment factors (Fig. 7). Table 5 presents the stresses at 2% total strain at ambient and sub-zero temperatures.

Table 5: Stress at 2% total strain at ambient and sub-zero temperatures in MPa

Temperature (°C)	High strength steel (G550)			Low strength steel (G300)		
	0.55 mm	0.75 mm	0.95 mm	0.55 mm	0.80 mm	1.0 mm
20	NA	671	605	341	347	318
-10	NA	678	619	377	375	350
-30	NA	715	638	405	409	379
-50	NA	732	672	456	467	444
-70	NA	781	727	529	538	532

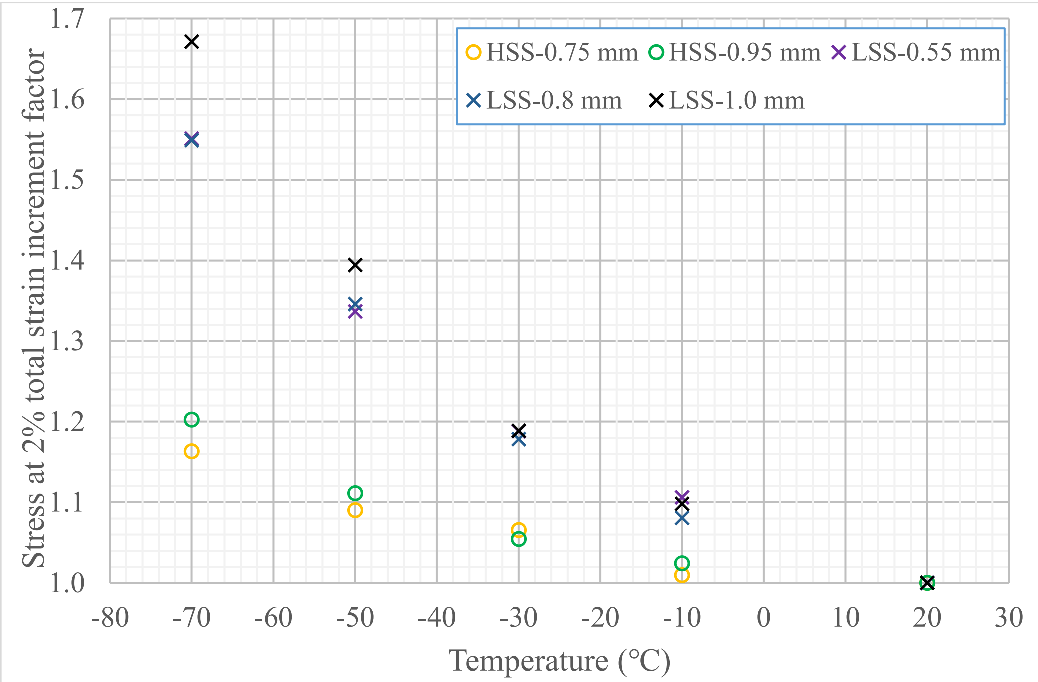


Fig. 11. Stress at 2% total strain increment factors of cold-rolled steel sheets

3.7. Ultimate and fracture strains

Ultimate and fracture strains are the most important strains to be determined from the experimental stress-strain curves. The former is used to create a theoretical stress-strain curve while the latter is used to determine the ductility of steel. Also, Eurocode 3 Part 1.3 [18] uses the ratio of ultimate strain to yield strain as one of the parameters to define ductility. Ambient and sub-zero temperature ultimate and fracture strains of cold-rolled steel sheets are shown in Figs. 12 and 13, respectively.

Ultimate strains of LSS are higher than those of HSS as corresponding fracture strains exhibit the same behaviour. Also, the ultimate strains of LSS and HSS -70 ℃ (other than 0.95 mm HSS) and 0.55 mm HSS at ambient to -50 ℃ are closer to the yield strain and are very small strains (less than 0.75%) as the stress-strain behaviour is similar to Fig. 4 (c). On the other hand, the fracture strains of 0.55 mm HSS and all the LSS do not change significantly up to -50 ℃ whereas the fracture strains of 0.75 mm and 0.95 mm HSS increase significantly up to -50 ℃.

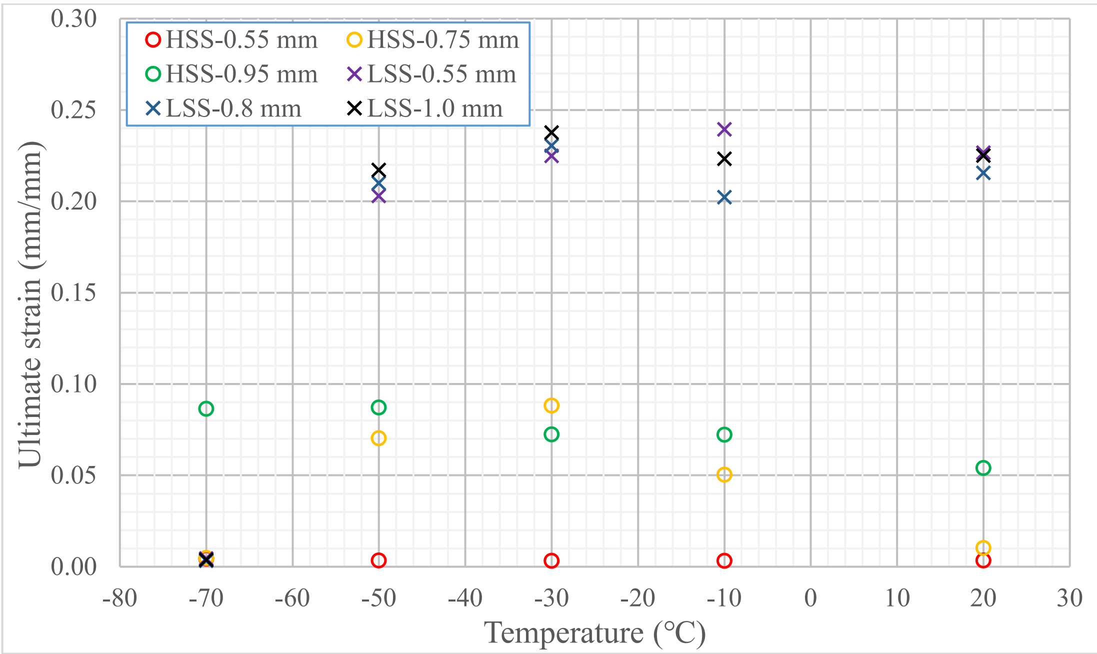


Fig. 12. Ultimate strains of cold-rolled steel sheets

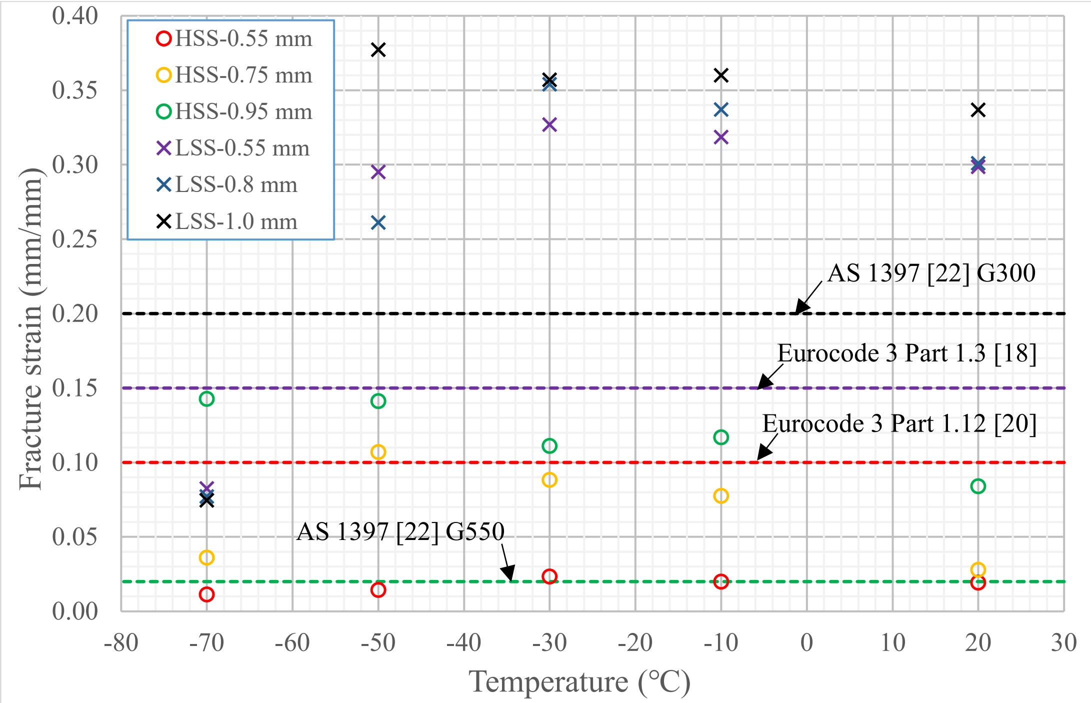


Fig. 13. Fracture strains (ε_f) of cold-rolled steel sheets

Fracture of structural steel elements depends on both ductility and toughness of steel. Ductility measures the ability to deform while toughness is defined as the ability to absorb energy. Eurocode 3 Part 1.1 [19] and Eurocode 3 Part 1.3 [18] give three ductility requirements, ie. ultimate strength to yield strength ($f_u/f_{0.2}$) ratio, fracture strain (ε_f) and ultimate strain to yield strain $(\varepsilon_u/\varepsilon_y)$ ratio should be greater than 1.10, 15% and 15, respectively. However, Eurocode 3 Part 1.12 [20] reduces the ductility requirements for high strength steel (S460 to S700). It reduces the $f_u/f_{0.2}$ ratio to 1.05 and ε_f to 10% while keeping the $\varepsilon_u/\varepsilon_y$ ratio limit at 15 (Figs. 13 and 14). However, it does not allow the use of plastic analysis and design for semi-rigid joints of high strength steels. Also, BS EN 10149 Part 2 [21] gives the minimum mechanical property requirements in such a way that they satisfy the ductility requirements of Eurocode 3 Part 1.12 [20]. However, AS 1397 [22] gives more relaxed ductility requirements (Table 6) than Eurocode 3 Part 1.12 [20]. On the other hand, AS/NZS 4600 [15] gives similar ductility requirements as Eurocode 3 Part 1.12 [20] for cold-formed steels that are not listed under AS 1397 [22] while it does not give any limits for $\varepsilon_u/\varepsilon_y$ ratio.

AS 1397 [22] gives the minimum fracture strains based on 50 mm gauge length for steels with thicknesses greater than 0.6 mm. Hence it cannot be used for both 0.55 mm G300 and G550 steels. Also, the minimum mechanical properties given in this standard can be used for G450, G500 and G550 steels with thickness greater than 1.5 mm, 1.0 mm to 1.5 mm and less than or equal to 1.0 mm, respectively. On the other hand, AS 1397 [22] does not give any $f_u/f_{0.2}$ ratio limits.

Table 6: Minimum mechanical properties in AS 1397 [22]

Steel grade	Min yield strength (MPa)	Min ultimate strength (MPa)	Minimum fracture strain (%)
G250	250	320	25
G300	300	340	20
G350	350	420	15
G450	450	480	10
G500	500	520	8
G550	550	550	2

Fig. 13 shows that HSS and LSS satisfy the minimum fracture strain requirement given in AS 1397 [22] except for LSS at -70 °C. However, LSS satisfy the minimum yield and ultimate strength requirements of G550 steel. Hence, it is questionable which minimum fracture strain is suitable. Fracture strains of LSS at -70 °C are greater than the requirement for G550 steel. Also, it is not possible to comment on the fracture strains of 0.55 mm LSS and HSS as their minimum values are not given in this standard.

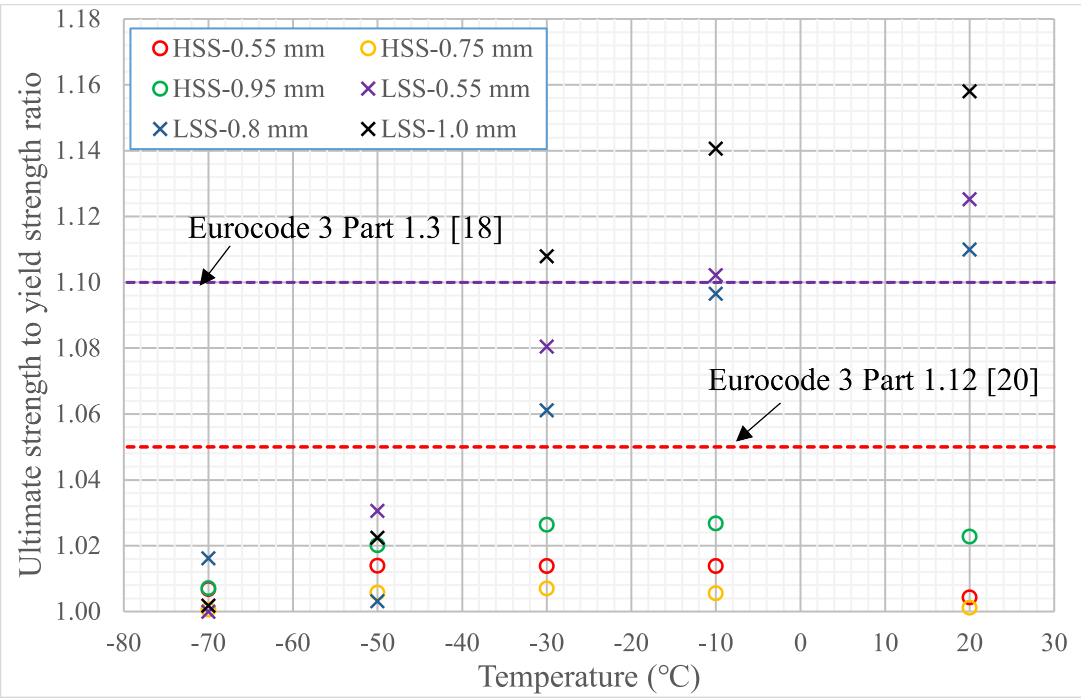


Fig. 14. Ultimate strength to yield strength ($f_u/f_{0.2}$) ratios of cold-rolled steel sheets

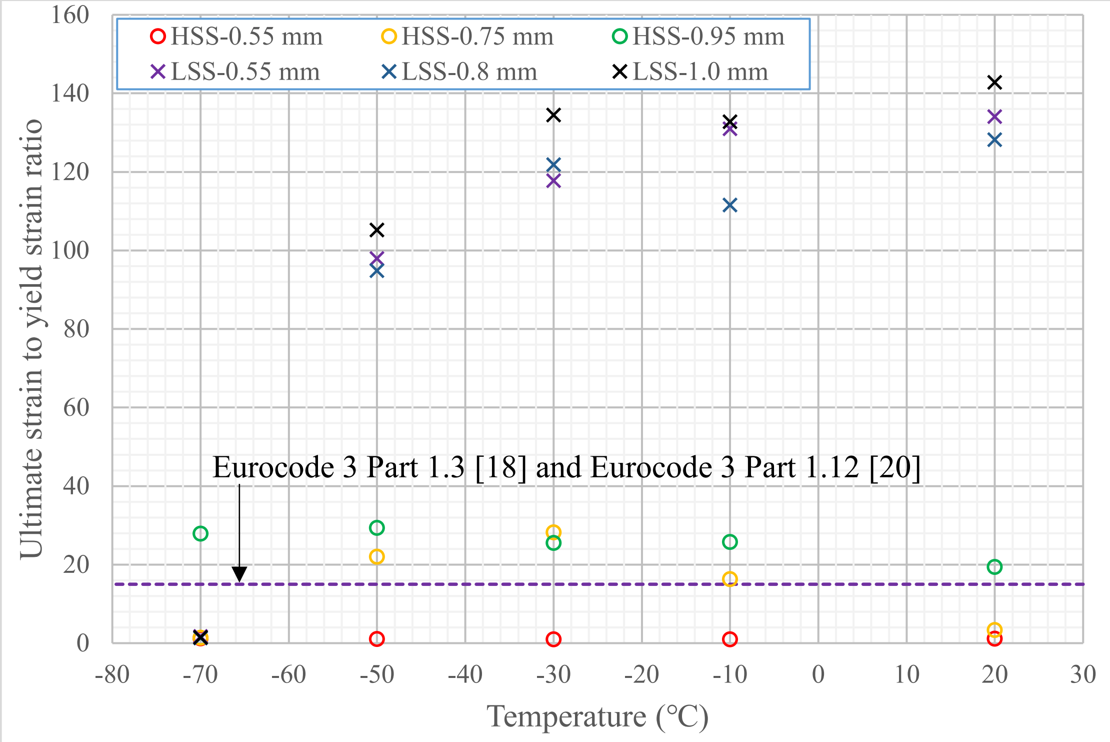


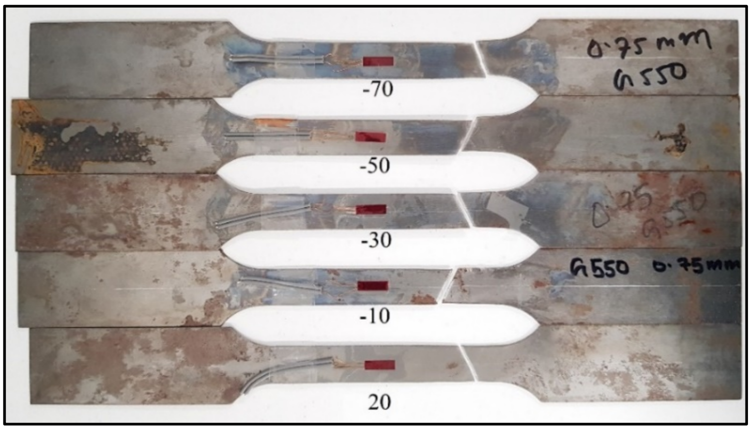
Fig. 15. Ultimate strain to yield strain $(\varepsilon_u/\varepsilon_y)$ ratios of cold-rolled steel sheets

LSS up to -50 °C satisfy the $(\varepsilon_u/\varepsilon_y)$ ratio and fracture strain requirements of Eurocode 3 Part 1.3 [18] (Fig. 15). LSS at -70 °C do not even satisfy the Eurocode 3 Part 1.12 [20] fracture strain requirement although they satisfy the minimum yield and ultimate strength requirements of S460 steel. On the other hand, HSS (other than 0.55 mm G550) satisfy the $(\varepsilon_u/\varepsilon_y)$ ratio requirement of Eurocode 3 Part 1.12 [20] while only 0.95 mm HSS within the temperature range of -10 °C to -70 °C and 0.75 mm HSS at -50 °C satisfy the fracture strain requirement. None of the HSS satisfy the $f_u/f_{0.2}$ ratio requirement of Eurocode 3 Part 1.12 [20] while 1.0 mm LSS up to -30 °C, 0.8 mm LSS at ambient temperature and 0.55 mm LSS up to -10 °C satisfy the $f_u/f_{0.2}$ ratio requirement of Eurocode 3 Part 1.3 [18]. Although LSS satisfy the $f_u/f_{0.2}$ ratio requirement of Eurocode 3 Part 1.12 [20] up to -30 °C, they do not satisfy the minimum yield and ultimate strength requirements of S460 steel.

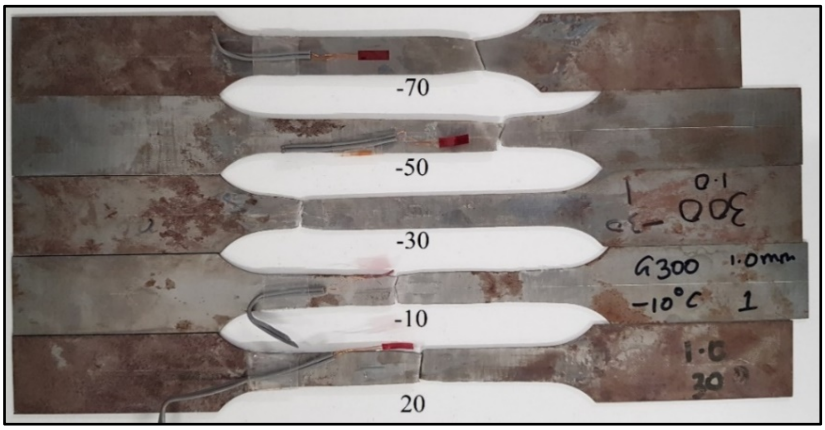
Hurlich [23] studied the sub-zero temperature behaviour of metals and showed that yield strength, ultimate strength, Young's modulus, fatigue resistance and hardness of metals increase as the temperature reduces. Also, metals with face-centred cubic structure, such as aluminium, silver and copper, remain ductile at sub-zero temperatures while metals with body-centred cubic structure, such as iron and chromium, show considerable reduction in ductility after the transition temperature. In addition, Hurlich [23] expressed that the rate of ultimate strength increment is less than that of yield strength increment for metals with body-centred cubic structure and that the ductility reduces as the reduced difference between yield and ultimate strengths reduces the fracture strain. Although the ultimate strength to yield strength ($f_u/f_{0.2}$) ratio of LSS reduces as the temperature drops, there is no reduction in fracture strain up to -50 °C. The increasing yield plateau of LSS with decreasing temperature helps to achieve higher fracture strains even though the $f_u/f_{0.2}$ ratio reduces.

AS/NZS 4600 [15] (for cold-formed steel not listed under AS 1397 [22]) and European steel design standards use the ratio of ultimate strength to yield strength ($f_u/f_{0.2}$) as one of the ambient and elevated temperature ductility parameters. As per this study, the $f_u/f_{0.2}$ ratio of LSS reduces with decreasing temperature while the fracture strain remains almost the same up to -50 °C (Figs. 13 and 14). Also, the $f_u/f_{0.2}$ ratios of 0.75 mm and 0.95 mm HSS remain almost the same while the fracture strain increases up to -50 °C. Therefore it is questionable whether the ductility of cold-formed steel sections can be quantified by the ratio of $f_u/f_{0.2}$ at sub-zero temperatures. If the $f_u/f_{0.2}$ ratio requirement is not considered as one of the ductility requirements, LSS up to -50 °C and 0.95 mm HSS within the temperature range of -10 °C to -70 °C can satisfy the ductility requirements given in European steel standards [18, 20].

Although the sub-zero temperature fracture strains of both LSS and HSS (other than 0.55 mm) satisfy the minimum fracture strain in AS 1397 [22], it is essential to determine the toughness of cold-formed steel at sub-zero temperatures prior to arriving at a firm conclusion on the use of cold-formed steel sections in sub-zero temperature environment. Steel toughness can be determined by Charpy V-notch impact tests based on AS 1544.2 [24] or ASTM A360-19 [17] or BS EN 10045 Part 1 [25]. The recommended specimen width is 10 mm in all three standards, however, the recommended minimum thickness is 2.5 mm in the first two standards while it is 5 mm in the third standard. Hence, specific testing requirements must be provided in these standards to determine the toughness of thin cold-formed steels. On the other hand, AS/NZS 4600 [15] does not allow the use of its design methods if the structure is subject to brittle failures while AS 4100 [26] controls the use of steel at sub-zero temperatures based on the notch toughness characteristics of steel. However, as per AS 4100 [26] the allowed minimum negative temperature increases with reducing steel thickness. This implies the possibilities of using cold-formed steel sections at sub-zero temperatures as their thicknesses are small.



a. 0.75 mm G500



b. 1.0 mm G300

Fig. 16. Fracture modes of tensile coupons

The stress-strain curves from repeated tests exhibit almost identical curves past the ultimate strain, but the fracture strain deviates in many cases. This may be because the fracture mechanism depends on the microstructure of the coupon while the other properties are based on the average behaviour across the cross-section of the coupon. Fracture modes of tensile coupons are shown in Fig. 16.

4. Comparison of mechanical properties with past research studies

In this section, sub-zero temperature mechanical property predictive equations given for other types of steels are discussed. There are no predictive equations given in Abdel-Rahim and Polyzois [3], who give only the mechanical properties at ambient temperature and -50 °C. Similarly, no predictive equations are given in Azhari et al. [8]. Hence the yield strength predictive equations given in Levings and Sritharan [5], Yan et al. [6] and Yan and Xie [7] are shown in Fig. 17 and compared with the results from this study.

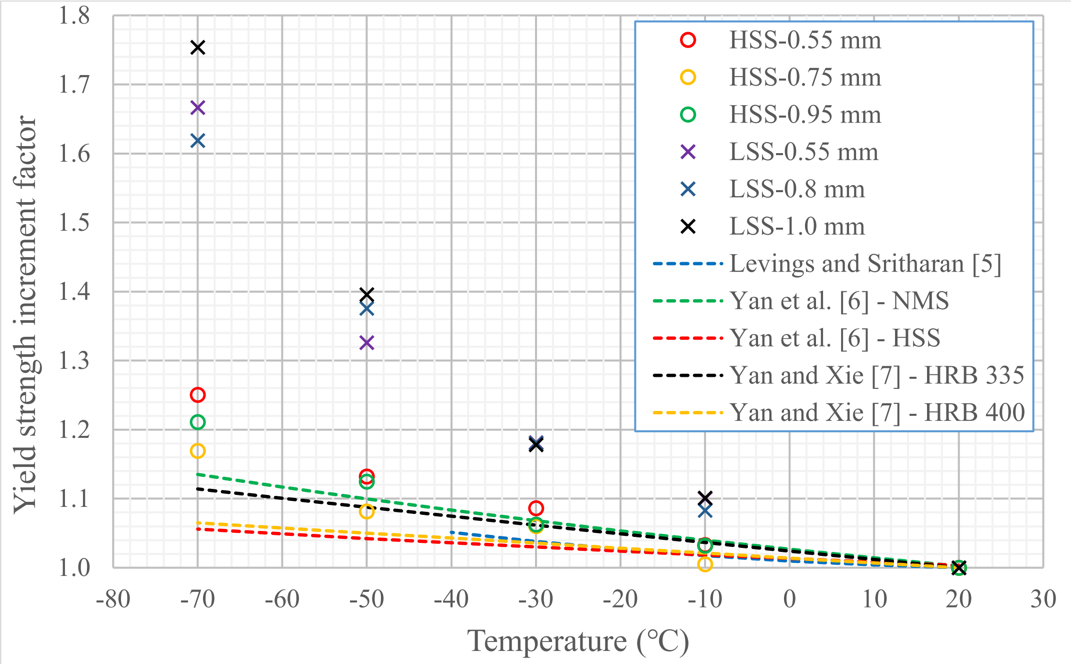


Fig. 17. Comparison of yield strength increment factors

Many past research studies of sub-zero temperature mechanical properties highlight that yield strength of steel increases as the temperature reduces. Yan et al. [6] states that the percentage yield strength increment of normal strength mild steel (NMS) is higher than that of HSS. Similarly, Yan and Xie [7] observed a higher percentage of increment in HRB335 reinforcement steel than in HRB400 reinforcement steel with a higher ambient temperature yield strength. This behaviour is reflected by their predictive equations too. Yield strength increment factors of other low strength steel types [6, 7] are closer to those of high strength cold-rolled steel sheets (HSS) obtained from this study. However, low strength cold-rolled steel (LSS) increment factors obtained from this study exhibit significant increment. Overall, cold-rolled steels show higher increment than other types of steel shown in Fig. 17. Ultimate strength increment factors of other steel types [5-7] show similar increment pattern as their yield strength increment factors. Hence, the increment factors of ultimate strength are not compared.

Young’s modulus predictive equations are not given in Levings and Sritharan [5] and Yan and Xie [7]. Levings and Sritharan [5] pointed out that Young’s modulus increment is not significant and neglected it. However, Yan et al. [6] provide predictive equations for Young’s modulus as shown in Fig. 18. The Young's modulus increment factors of both NMS and HSS given in Yan et al. [6] are closer to those of cold-rolled steel sheets obtained from this study.

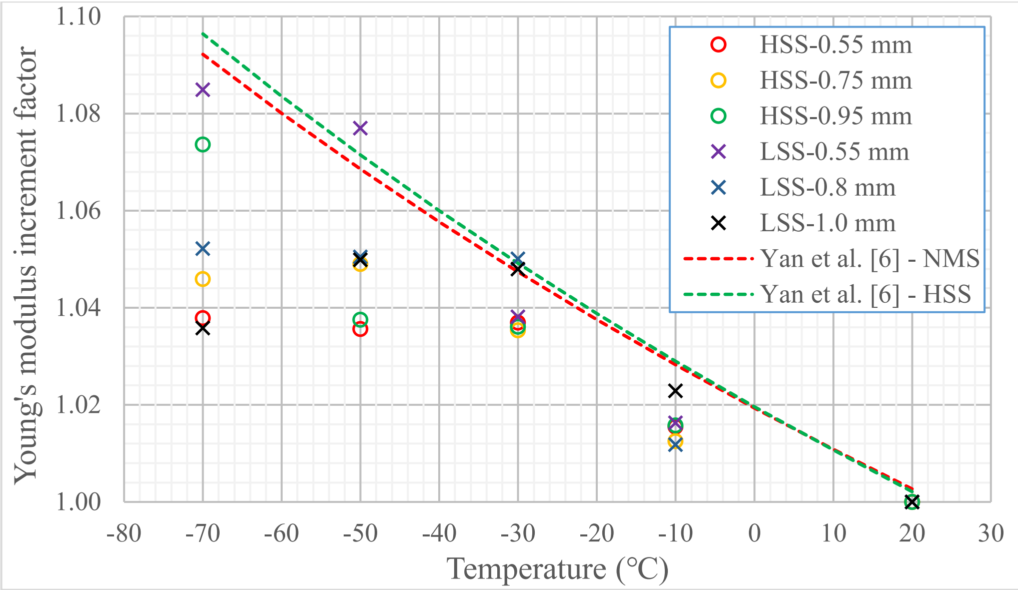


Fig. 18. Comparison of Young's modulus increment factors

No predictive equations are given for the fracture strain of other steels at sub-zero temperatures [5-7]. Also, the fracture strain does not show a uniform trend in reduction or increment. Yan et al. [6] reported that fracture strain increases as the temperature drops, similar to the results of this study. Nevertheless, Abdel-Rahim and Polyzois [3], Yan and Xie [7] and Azhari et al. [8] reported that the fracture strain reduces as the temperature reduces. However, they did not observe the sudden drop in fracture strain similar to that observed at -70 °C. On the other hand, Levings and Sritharan [5] did not discuss the fracture strain. The different behaviour of fracture strain among the steel types may be due to the different transition temperatures at which the steel behaviour changes from ductile to brittle.

5. Predictive equations

5.1 Mechanical Properties

Sub-zero temperature tensile tests are difficult to conduct due to their cost and safety issues. Hence, it is essential to develop sub-zero temperature mechanical property predictive equations of cold-rolled steel sheets using their ambient temperature mechanical properties for use by engineers and researchers. This paper proposes suitable predictive equations for the sub-zero temperature mechanical property increment factors of yield strength, Young's modulus, ultimate strength and stress at 2% total strain in the temperature range of -70 °C to ambient temperature. The temperature dependent (T in °C) increment factors are given as ratios of sub-zero temperature and ambient temperature mechanical properties. However, predictive equations are not proposed for ultimate and fracture strains as the sub-zero temperature strain to ambient temperature strain ratios do not show a regular pattern. Also, the ultimate and fracture strains depend on the steel grade and thickness.

Separate yield strength, upper yield strength, ultimate strength and stress at 2% total strain predictive equations are proposed for LSS and HSS as they show different incremental patterns. However, the same equation is given for LSS and HSS Young's modulus increment factors since differences are small. Importantly, the ambient temperature Young's modulus can be conservatively used at sub-zero temperatures since Young's modulus increases only slightly with reducing temperature. Linear equations are not suitable for sub-zero temperature mechanical property increment factor predictive equations as actual variations are of quadratic or cubic incremental pattern. Hence, quadratic equations (2) are proposed except for the ultimate strength increment factor of LSS, for which a cubic equation (3) is proposed.

$$f_T/f_{20} = a \times 10^{-5}\, T^2 + b \times 10^{-3}\, T + c \qquad (2)$$

$$f_T/f_{20} = -1.8 \times 10^{-6}\, T^3 - 6.2 \times 10^{-5}\, T^2 - 1.8 \times 10^{-3}\, T + 1.075 \qquad (3)$$

where, T is temperature in °C, a, b and c are coefficients given in Table 7, f_T and f_{20} are the mechanical properties at sub-zero temperature T and ambient temperature, respectively.

Figs. 19 to 23 exhibit a good comparison between the proposed equations and experimental results and thus confirm the suitability of using Equations 2 and 3 with their associated coefficients a, b and c given in Table 7 in predicting the sub-zero temperature increment factors for yield strength, Young's modulus, upper yield strength, ultimate strength and stress at 2% total strain.

Table 7: Coefficients a, b and c for Equations 2 and 3

Mechanical property	Steel type	a	b	c
Yield strength	LSS	8	-3	1.028
	HSS	3	-1	1.008
Young's modulus	LSS & HSS	0.2	-0.5	1.009
Upper yield strength	LSS	7	-5.2	1.076
	HSS	2.6	-1.4	1.018
Ultimate strength	LSS	Refer to Equation 3		
	HSS	2	-1	1.012
Stress at 2% total strain	LSS	6	-3.1	1.038
	HSS	2	-0.9	1.010

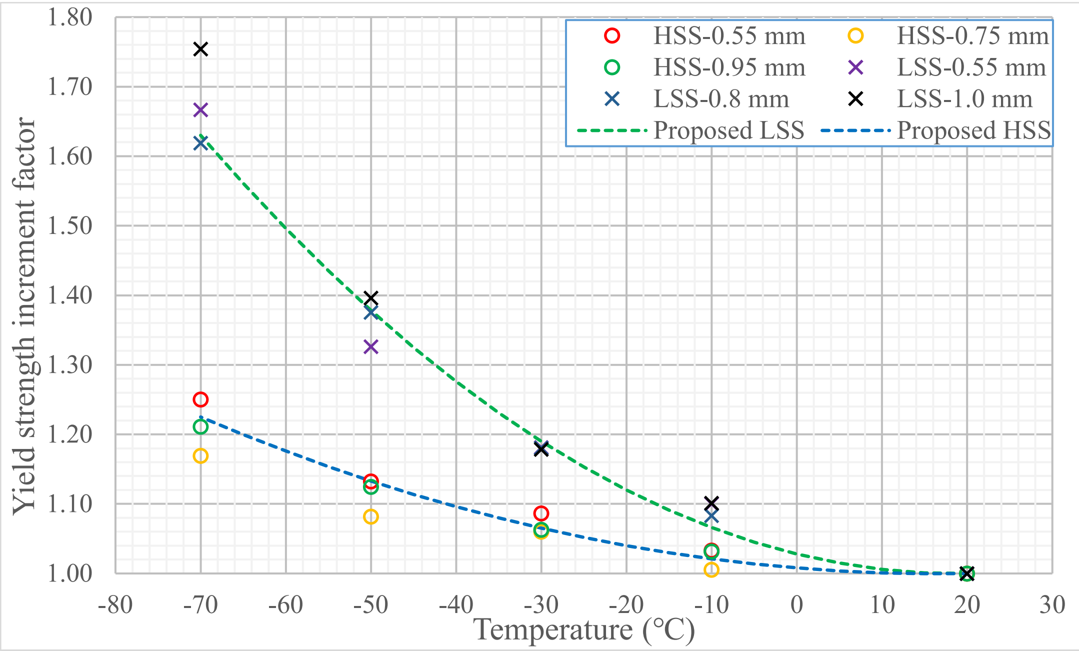


Fig. 19. Comparison of experimental results with predictive equations for yield strength

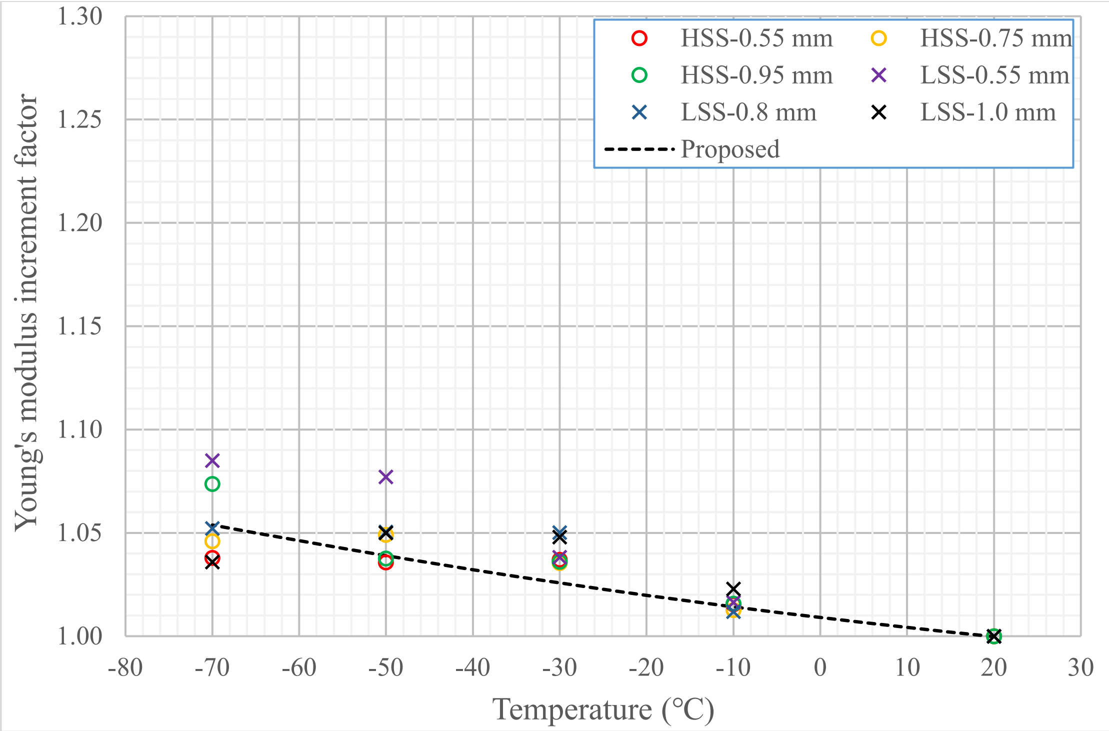


Fig. 20. Comparison of experimental results with predictive equations for Young's modulus

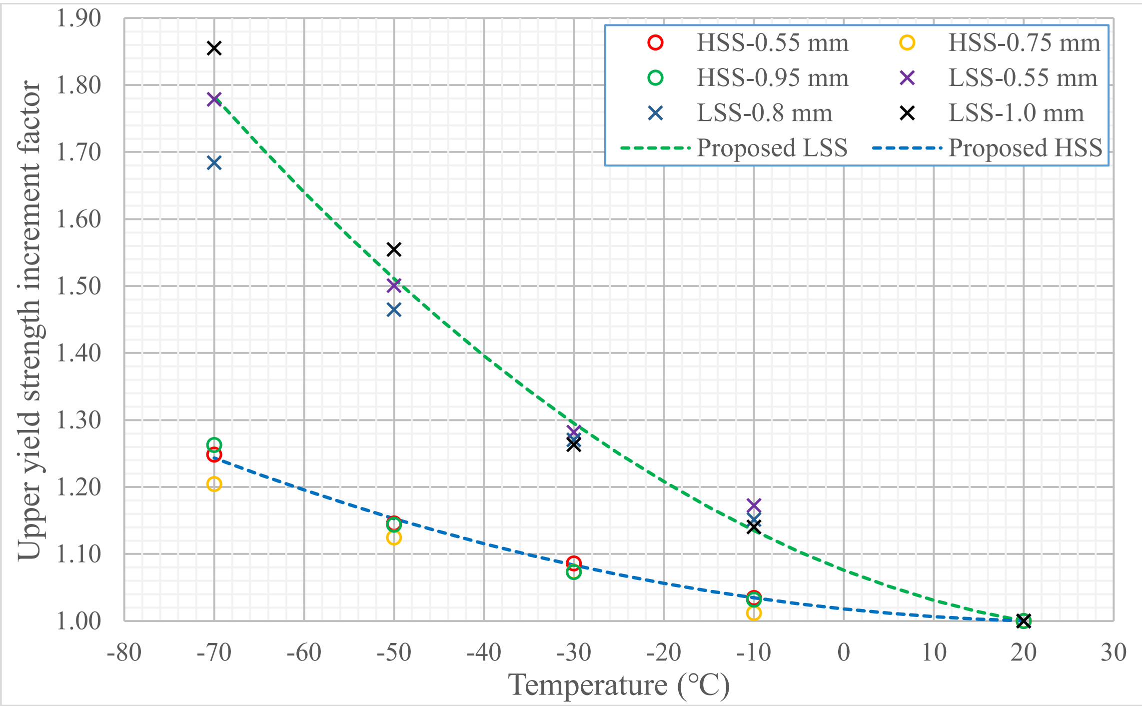


Fig. 21. Comparison of experimental results with predictive equations for upper yield strength

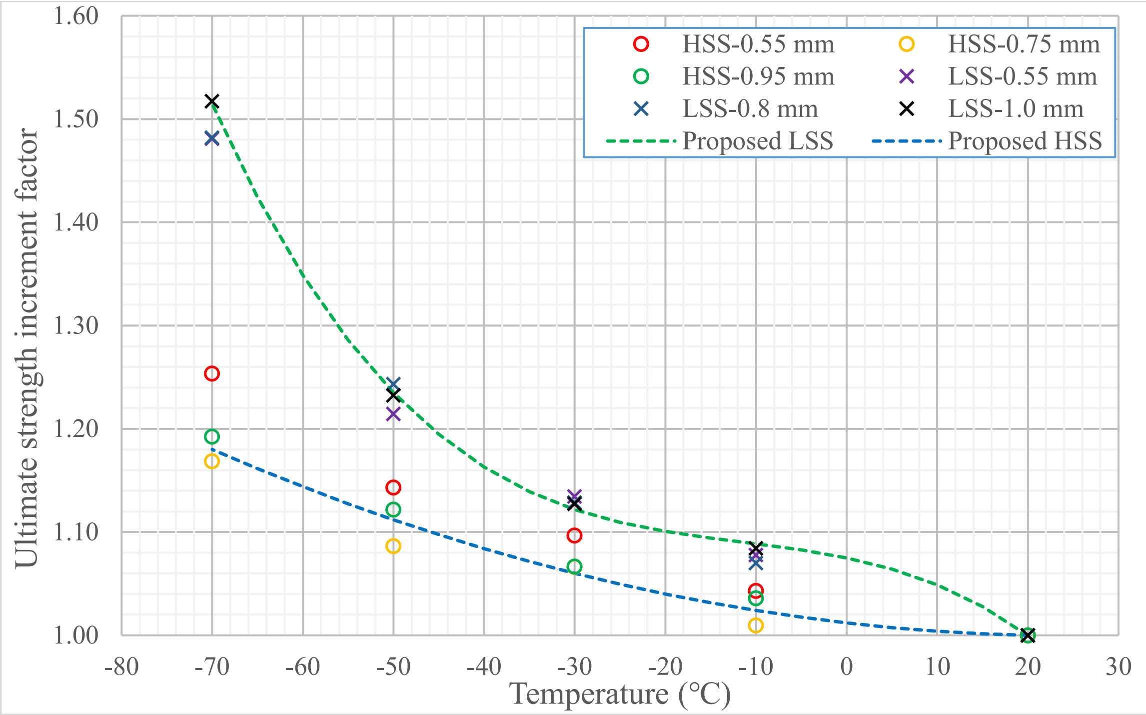


Fig. 22. Comparison of experimental results with predictive equations for ultimate strength

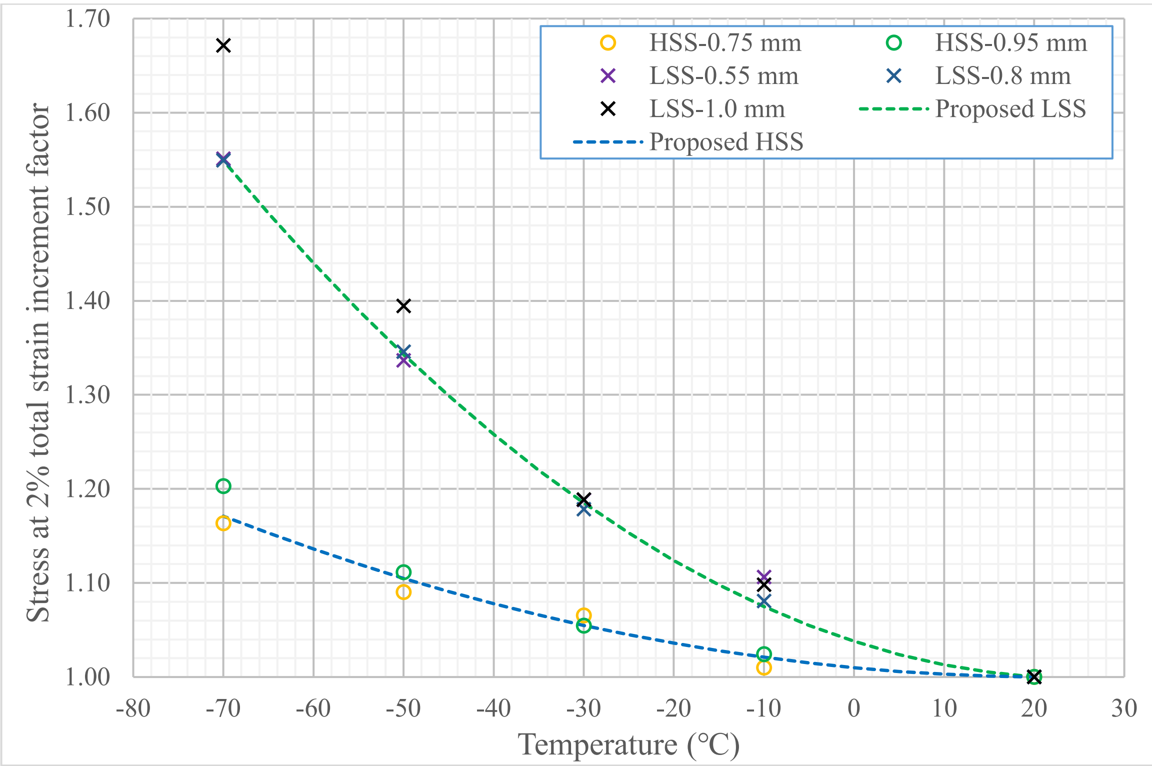


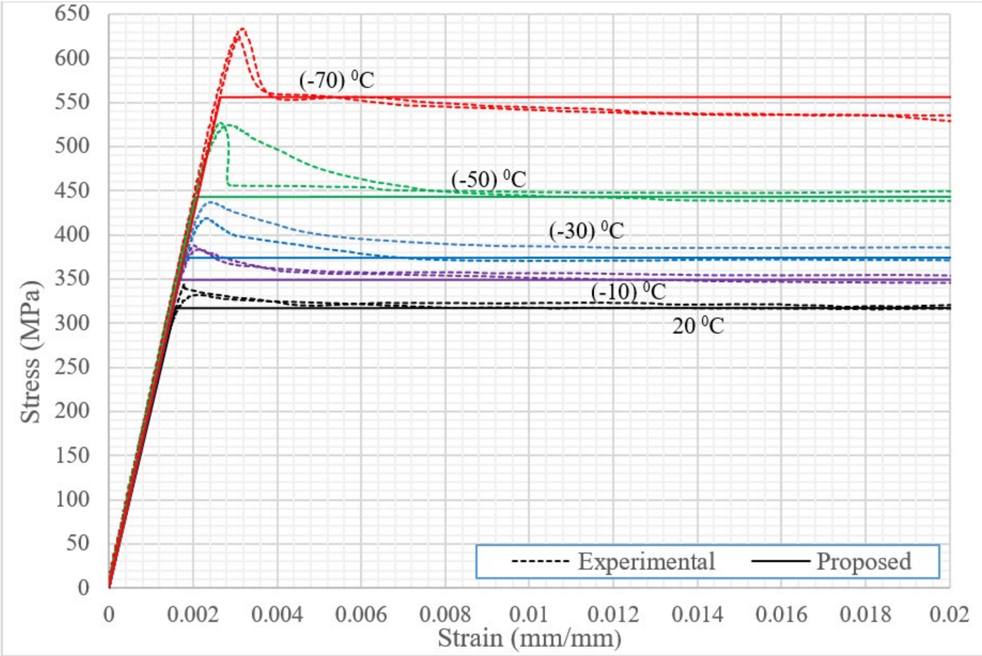
Fig. 23. Comparison of experimental results with predictive equations for stress at 2% total strain

The mechanical property increment factors proposed in this paper for cold-rolled steel sheets can be used for cold-formed steel channel sections and floor decks used in composite constructions as they are subject to low levels of cold working. Also, cold-rolled steel sheets and cold-formed steel sections did not show much variation in their elevated temperature reduction factors [10]. However, the applicability of these predictive equations to cold-formed steel hollow sections needs to be verified as they are subject to higher levels of cold working and welding. Hollow sections show different elevated temperature mechanical property reduction factors compared with cold-rolled steel sheets and cold-formed open steel sections [13].

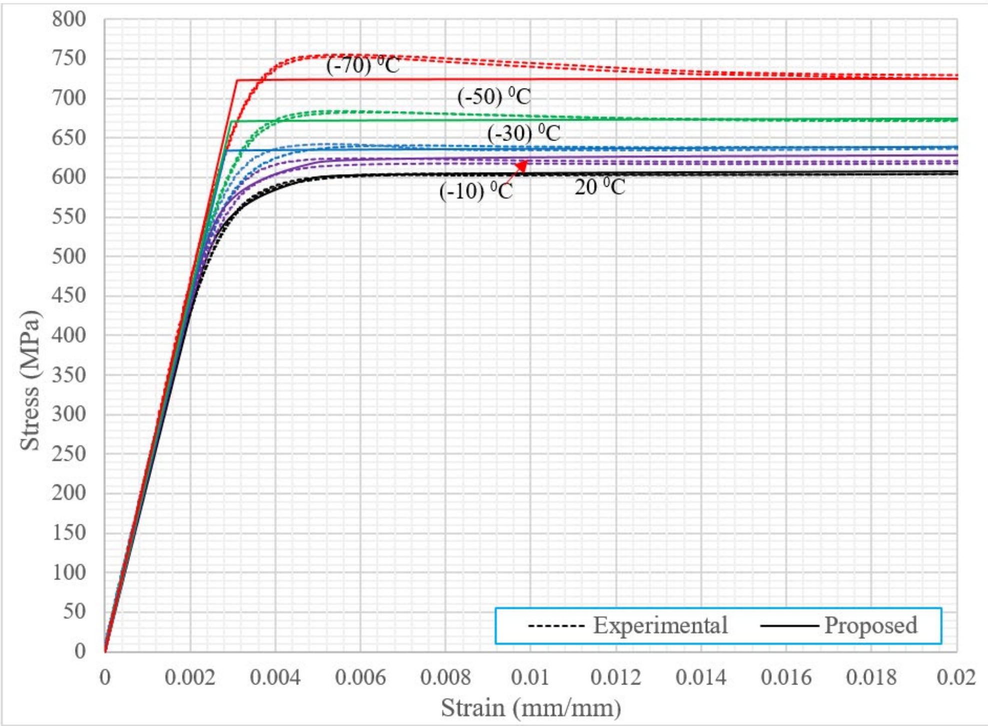
5.2 Stress-strain curves

Cold-formed steel design standards use mechanical properties in their capacity predictive equations. Hence, stress-strain curves are rarely used by engineers. However, design standards have been encouraging the use of advanced analysis in recent years, for example, Appendix B and fire section of AS/NZS 4600 [15]. Advanced analysis is also widely used for research purposes. For this purpose accurate stress-strain curves are needed.

Based on the experimental stress-strain curves presented in the previous sections, it is recommended that elastic perfect plastic stress-strain model can be used for cold-rolled steel sheets at ambient and sub-zero temperatures except for HSS at ambient temperature. For the latter, the two-stage stress-strain model given in Rokilan and Mahendran [10] is recommended. Fig. 24 shows the comparison between the recommended and experimental stress-strain curves of low and high strength cold-rolled steel sheets. Cold-rolled steel sheets exhibit linear stress-strain response up to yield strength or upper yield strength at ambient and sub-zero temperatures except for HSS at ambient temperature. Although LSS exhibits strain hardening, there is a significant yield plateau prior to strain hardening. Hence, it is better to use elastic perfect plastic stress-strain model. Also, AS/NZS 4600 [15] recommends the use of elastic perfect plastic stress-strain model for LSS at temperatures less than 300 °C. On the other hand, HSS does not show significant nonlinearity or strain hardening at sub-zero temperatures. Hence, elastic perfect plastic stress-strain model agrees well with the experimental stress-strain curves.



a. G300 – 1.0 mm



b. G550 – 0.95 mm

Fig. 24. Comparison of experimental and recommended stress-strain curves

6. Conclusion

In this research, a detailed experimental study was conducted to determine the sub-zero temperature mechanical properties of low and high strength cold-rolled steel sheets. Following are the main findings and recommendations of this research.

1. Yield strength, upper yield strength, ultimate strength and stress at 2% total strain of cold-rolled steel sheets increase with reducing temperature while low strength steels (LSS) show higher increment than high strength steels (HSS). Also, the ultimate strength to yield strength ratio of LSS significantly reduces with reducing temperature.
2. Fracture strains of LSS and 0.55 mm HSS cold-rolled steel sheets do not change significantly up to -50 °C while those of 0.75 mm and 0.95 mm HSS significantly increase up to -50 °C. However, the fracture strains of all the steels except 0.95 mm HSS reduce considerably at -70 °C.
3. All the tested cold-rolled steel sheets satisfy the ductility requirements of AS/NZS 4600 [15] as they satisfy the fracture strain requirements in AS 1397 [22] except for LSS at -70 °C and 0.55 mm LSS and HSS. However, LSS satisfy the minimum yield and ultimate strength and fracture strain requirements of G550 steel. On the other hand, none of the HSS satisfies the ductility requirements of Eurocode 3 Part 1.12 [20] while only 1.0 mm LSS up to -30 °C, 0.8 mm LSS at ambient temperature and 0.55 mm LSS up to -10 °C satisfy the ductility requirements of Eurocode 3 Part 1.3 [18].
4. Although the tested cold-rolled steel sheets satisfy the ductility requirements given in AS/NZS 4600 [15], fracture of steel member depends on toughness also. Hence, the toughness of cold-rolled steel sheets at sub-zero temperature should be compared with that at ambient temperature in relation to the use of cold-formed steels in sub-zero temperature environment. Toughness can be determined using Charpy V-notch impact tests. However, the minimum thickness is given as 2.5 mm in the testing standards. Appropriate modifications are needed for the testing of thin cold-formed steels.
5. Cold-rolled steels exhibit higher increment in yield and ultimate strengths than the other steel types [5-7] while Young's modulus increment of cold-rolled steels is similar to other steel types.
6. New predictive equations are proposed to predict the sub-zero temperature (up to -70 °C) mechanical properties such as yield strength, Young's modulus, upper yield strength, ultimate strength and stress at 2% strain, based on their ambient temperature

mechanical properties. The proposed increment factor predictive equations can also be used for open cold-formed steel sections. The predictive equations are given up to -70 °C as the minimum recorded temperature in the Arctic region was -68 °C.

7. Elastic perfect plastic stress-strain model can be used for ambient and sub-zero temperature stress-strain curves of cold-rolled steel sheets except for HSS at ambient temperature, for which the two-stage stress-strain model given in Rokilan and Mahendran [10] can be used.

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