Mechanical Properties of Cold-formed Steels at Elevated Temperatures

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Abstract

Mechanical properties have an important role in the fire safety design of cold-formed steel structures due to the rapid reduction in mechanical properties such as yield strength and elastic modulus under fire conditions and associated reduction to the load carrying capacities. Hence there is a need to fully understand the deterioration characteristics of yield strength and elastic modulus of cold-formed steels at elevated temperatures. Although past research has produced useful experimental data on the mechanical properties of cold-formed steels at elevated temperatures, such data does not yet cover different cold-formed steel grades and thicknesses. Therefore an experimental study was undertaken to investigate the elevated temperature mechanical properties of two low and high strength steels with two thicknesses that are commonly used in Australia. Tensile coupon tests were undertaken using a steady state test method for temperatures in the range of 20 to 700°C. Test results were compared with the currently available reduction factors for yield strength and elastic modulus, and stress-strain curves, based on which further improvements were made. For this purpose, test results of many other cold-formed steels were also used based on other similar studies undertaken at the Queensland University of Technology. Improved equations were developed to predict the yield strength and elastic modulus reduction factors and stress-strain curves of a range of cold-formed steel grades and thicknesses used in Australia. This paper presents the results of this experimental study, comparisons with the results of past research and steel design standards, and the new predictive equations.

Keywords: Cold-formed steels, elevated temperatures, mechanical properties, reduction factors, yield strength, elasticity modulus, stress-strain model, fire safety design

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1 Introduction

Fire safety of cold-formed steel buildings has received greater attention in recent times due to increasing usage of cold-formed steel members in residential, commercial and industrial buildings. With increasing temperatures during fire events, the mechanical properties of cold-formed steels deteriorate rapidly, resulting in the loss of load bearing capacity of cold-formed steel members. Hence a good knowledge and understanding of the deterioration characteristics of the mechanical properties with increasing temperatures is essential for the fire safety design of cold-formed steel structures. BS5950 Part 8 [1] and Eurocode 3 Part 1.2 [2] provide suitable reduction factors for the mechanical properties of cold-formed steels at elevated temperatures. However, BS5950-Part 8 provides the reduction factors for yield strengths corresponding to 0.5%, 1.5% and 2.0% strain levels although the common practice is to use 0.2% proof stress as the yield strength. Further, it does not provide any reduction factors for elastic modulus at elevated temperatures. On the other hand, Eurocode 3 Part 1.2 [2] provides the same yield strength and elastic modulus reduction factors for both hot-rolled and cold-formed steels despite the fact that the reduction of mechanical properties is considered to be different. Sidey and Teague [3] concluded that the strength reduction of cold-formed steels at elevated temperatures may be 10-20% higher than that of hot-rolled steels due to the metallurgical composition and molecular surface effects. At elevated temperatures, cold-formed steels are also likely to lose their strength that they gained through cold-working process at ambient temperature.

Past research on the mechanical properties at elevated temperatures was mainly focussed on hot-rolled steels. However, in recent times some studies have been undertaken for cold-formed steels [4-6]. In addition to them, a series of experimental studies was also undertaken on the mechanical properties of Australian cold-formed steels of varying thicknesses and grades at the Queensland University of Technology (QUT) [7-10]. The study conducted by Lee et al. [7] was later found to have some inaccuracies in terms of the strain and temperature measurements. Ranawaka and Mahendran [8] eliminated these shortcomings and developed improved predictive equations for the mechanical properties of thinner cold-formed steels. They showed that yield strength and elastic modulus reduction factors presented by other researchers are not suitable for the cold-formed steels used in Australia. Despite these improvements made through the experimental studies at QUT, they were mostly limited to

thinner steels (up to 1.0 mm). Therefore an experimental study was undertaken to determine the elevated temperature mechanical properties of more commonly used cold-formed steels, 1.55 mm and 1.95 mm G250 and 1.50 mm and 1.90 mm G450 steels with a minimum yield strength of 450 MPa. Steady state tensile coupon tests of these steels were undertaken at elevated temperatures in the range of 20 to 700°C using an advanced strain measurement technique based on Laser Speckle Extensometer. The results of mechanical properties and stress-strain curves obtained from this study were combined with all the available results from other QUT studies for G250, G500 and G550 steels with minimum yield strengths of 250, 500 and 550 MPa, and improved equations were developed for the prediction of yield strength, elastic modulus and stress-strain curves of cold-formed steels used in Australia.

This paper presents the details of this experimental study, the results, and comparison of the results with the currently available reduction factors of mechanical properties obtained from past research as well as from steel design codes. It also includes the details of the improved predictive equations developed in this study for Australian cold-formed steels.

2 Experimental Investigation

2.1 Test Method

The most commonly used method to assess the mechanical properties of steels is to perform tensile coupon tests based on either the steady state or the transient state test method. Although the transient state test method is considered to be more realistic in simulating the behaviour of a real fire including the creep effect, the steady state test method is commonly used as it is easier to conduct than the transient state test method and provides the stress-strain curves directly [6-8]. The creep effect is also considered negligible since both steady state and transient state tests are usually completed within an hour. Hence in this research the steady state test method was used. In this method, the specimen is heated up to the required temperature and then a tensile load is applied at a constant rate either as strain controlled or load controlled until failure while maintaining a constant temperature. In this study the tensile coupon tests were conducted under strain control. Tensile coupon tests were conducted to determine the mechanical properties of 1.55 and 1.95 mm G250 steels and 1.50 and 1.90 mm G450 steels at pre-selected uniform temperatures from ambient temperature to 700$^{\text{o}}$C. This

study also included some elevated temperature tests of 0.95 mm G550 steels to complement the results provided by Ranawaka and Mahendran [8] for G550 steels.

2.2 Test Specimen

Test specimens were cut in the longitudinal direction of cold-formed steel sheets. The shapes and sizes of specimens were in accordance with AS 1391 [11] (Figure 1). A hole was provided at each end of the specimen in order to fix it to the loading shafts located at the top and bottom ends of the furnace using M10 bolts.

The coating of each specimen was removed by immersing it in diluted hydrochloric acid. The specimen's base metal thickness and width were then measured at three points within the gauge length using a micrometer and a vernier calliper, respectively. The averages of these measured dimensions were used in the calculations of mechanical properties.

2.3 Test Rig and Procedure

Tensile coupon tests at elevated temperatures were carried out inside an electrical furnace heated by four glow bars (Figure 2). The two thermocouples located inside the furnace gave the air temperature of the furnace. An additional thermometer was placed in contact with the specimen to measure its temperature.

Eight temperatures were selected in this study: 20°C, 100°C, 200°C, 300°C, 400°C, 500°C, 600°C and 700°C. For Grade 450 steels, 450°C and 550°C were also selected. At least two tests were carried out for each temperature. Initially, the temperature inside the furnace was increased to a pre-selected value with the specimen inside the furnace using a heating rate of 10-20°C/min. It was observed that the specimen temperature measured by the thermometer differed from the air temperature measured by the thermocouples by about 10 to 20°C. This difference was dependant on the pre-selected temperature and was due to the radiative heating of the glow bars. Therefore the temperature shown by the thermometer was used as the specimen temperature. After reaching the pre-selected temperature, it was allowed to remain for 10 minutes before applying the loading in order to ensure a uniform temperature within the specimen. During the heating phase, the specimen was maintained under a small tensile load while allowing free upward movement caused by thermal expansion. Once the specimen

stabilized at the required temperature, a tensile load was applied at a constant strain rate until failure. The displacement rate used was 0.15 mm/min, which was equivalent to a strain rate of 0.000042/s and satisfied the requirement of SFS-EN100002-5 [12] and AS 2291 [13].

Figure 2 shows the details of the tensile test set-up. The specimen was connected to two vertical end rods, which were accurately aligned with each other. The bottom end was fixed while the top end was free to move upwards. The tensile load was applied by using a hydraulic actuator connected to the top end rod. The Multi-purpose TestWare System was used as the data logger and was also used to control the hydraulic actuator. The applied load was measured by using a load cell of 1 tonne for high temperatures and a load cell of 5 tonnes for low temperatures.

Since it was not possible to use strain gauges at elevated temperatures, a contact free laser speckles extensometer (Figure 2) developed by Austrian Company Messphysik GmbH was used to measure the strains of the tensile test specimens. The laser speckle extensometer was located behind the furnace so that the cameras can be directed to the specimen gauge length through the fire resistant window of the furnace (Figure 2). Two laser beams were directed to two points on the specimen (Figure 2). The laser speckle extensometer measured the relative displacement of these two points and thereby calculated the strain in the specimen. The measurement principles of extensometer are discussed in detail in Ranawaka and Mahendran [8].

Firstly, the tensile coupon tests were carried out at ambient temperature. In this case the strain was measured by using both 5 mm strain gauges and the laser speckle extensometer. The stress-strain curves obtained were in good agreement confirming that the strain measurements of the laser speckle extensometer are accurate. The results of yield strength and elastic modulus obtained from both strain gauges and the laser speckle extensometer at ambient temperature are in good agreement (Table 1). Hence all the elevated temperature tensile coupon tests were carried out by using the laser speckle extensometer. Table 1 also includes the ambient temperature mechanical properties of cold-formed steels (G250, G500 and G550) used in other QUT studies [8-10].

3 Results and Discussion

3.1 Yield Strength

Figures 3 (a) and (b) show the comparison of stress-strain curves for 1.95 mm G250 and 1.90 mm G450 cold-formed steels at elevated temperatures. The stress-strain curves of G250 steel show a linear elastic region followed by a well defined yield plateau at ambient temperature. Temperatures at 100°C and 200°C show similar kind of stress-strain curves but do not exhibit a smooth yield plateau as for ambient temperature. In these cases, the yield strength was taken as the average value of stresses in the plateau. At temperatures beyond 200°C the stress-strain curves of G250 steel were of the gradual yielding type. Unlike the low strength steel (G250), the high strength steel (G450) gave gradual yielding type stress-strain curves at both ambient and elevated temperatures. Due to the absence of a well defined yield point, the 0.2% proof stress was taken as the yield strength for gradual yielding type stress-strain curves. In addition, the stresses at 0.5%, 1.5% and 2.0% strain levels were also determined from the intersection of stress-strain curve and a non-proportional vertical line at the specified strain values. The reduction factors of yield strength at elevated temperatures were calculated as the ratio of yield strength at elevated temperatures, $\sigma_{y,T}$, to that at ambient temperature, $\sigma_{y,20}$, given in Table 1. Table 2 gives the yield strength reduction factors for different strain values at different temperatures.

Figure 4 demonstrates that the yield strength reduction characteristics of low and high strength steels are different. For high strength steels (G450), the reduction factors were high for temperatures up to 500°C (ie. less reduction in yield strength), but were low for temperatures above 500°C compared with low strength steels. It appears that the yield strengths of G450 steels do not decrease much up to 200°C. Unlike G450 steels, G250 steels lose their yield strengths at a lower rate up to 200°C and thereafter decrease at a rapid rate. Comparatively, G450 steels lose their yield strength more rapidly than G250 steels in the temperature range of 300°C to 600°C. Figure 4 shows that the specimen thickness does not have much influence on the yield strength reduction factors of both steels.

Figures 5 (a) and (b) show the variation of reduction factors with strain levels for low and high strength steels, respectively. It is interesting to note that the yield strength reduction factors based on 0.5% total strain are closer to those based on 0.2% proof stress, for both low

and high strength steels. Similar observation was also made by Ranawaka and Mahendran [8]. Both G250 and G450 steels show higher yield strength reduction factors for yield strengths based on higher strain levels (1.5% and 2.0%). The yield strength corresponding to 1.5% and 2.0% strain levels was very close to the ultimate strength in some cases, especially for G450 steel. Therefore it is not safe to use the stresses based on 1.5% or 2.0% total strain as the yield strength for design purposes. Based on these, it is recommended that either 0.2% proof stress or stress at 0.5% total strain is used as the yield strength at elevated temperatures.

3.2 Elastic Modulus

Elastic modulus was calculated from the initial slope of the stress-strain curve. The reduction factor was then calculated as the ratio of the elastic modulus at elevated temperature (E_T) to that at ambient temperature (E_{20}) given in Table 1. The reduction factors calculated based on the average measured values of elastic modulus at different temperatures for both low and high strength steels are presented in Table 3.

Figure 6 shows that the elastic modulus of cold-formed steel decreases in a similar trend irrespective of steel grades and thicknesses. In most cases the discrepancy in the reduction factors of elastic modulus at a particular temperature is less than 10%. Therefore it is considered that the effect of steel thickness and grade on the reduction factors of elastic modulus at elevated temperatures is insignificant.

3.3 Ultimate Strength

The ultimate strength reduction factors were calculated based on the ratio of ultimate strength at a particular temperature ($\sigma_{u,T}$) to that at ambient temperature ($\sigma_{u,20}$) given in Table 1. They are given in Table 4. The ultimate strength factors of G250 and G450 steels are closer to each other except at 200°C and 300°C. The effect of thickness was found to be insignificant for both steels as shown in Figure 7.

It is interesting to note that there is almost 20% increase in the ultimate strength of low strength steel at 200°C compared to that at ambient temperature. Increase in the ultimate strength of low strength steel can be attributed to the transformations taking place in the steel base at low temperatures. At lower temperatures, the effect of transformations taking place is predominant compared to the reduction of ultimate strength due to temperature increase. With

increasing temperature, these transformations are retarded and therefore the ultimate strength reduces. The ultimate strengths of high strength steels are also slightly higher compared to that at ambient temperature. Because of the same chemical composition of both types of steel, high strength steels also exhibit the transformation of steel base at low temperatures, which leads to increase in the ultimate strength. However, parallel with the increase of ultimate strength due to these transformations, the strength increase due to cold-working drops with increasing temperature. Therefore the increase in ultimate strength at low temperatures is not significant as for low strength steel.

3.4 Ductility

Ductility of steel is defined based on the level of deformation that steel can undergo plastically before fracture. In this study, tensile strains were measured until fracture and the resulting stress-strain curves are plotted in the same graph for different temperatures in Figures 8 (a) and (b) for low and high strength steels, respectively. The effect of temperature and the steel grade on the ductility of steel were studied by comparing the strain values at fracture.

Low strength steel (G250) shows higher ductility than high strength steel (G450) at ambient temperature. This can be attributed to the comparatively high strain hardening caused by cold working in the case of G450 steel. However, G250 steel has reduced ductility at temperatures in the range of 100°C to 500°C compared to that at ambient temperature while its ductility increased beyond 600°C. For both steels, the lowest ductility was at 100°C and their ductility at 100°C was reduced by about 50% compared to ambient temperature. However, it improved when the temperature was increased beyond 100°C for both G250 and G450 steels. At 450°C the ductility of G450 steel decreases significantly compared to 400°C and thereafter it starts to improve again. Decrease in ductility at 100°C can be attributed to chemical transformations taking place in the steel base. With increasing temperature, these chemical transformations retard and ductility of steels increases when temperature becomes predominant.

Typical failure modes for 1.95 mm G250 and 1.90 mm G450 cold-formed steels at different temperatures are shown in Figures 9 (a) and (b), respectively. Up to 300°C, G450 steels showed less ductile failures (brittle with no necking) and thereafter their failures became more ductile. Brittle failure was seen in G250 steel only at 100°C and it shows some ductile

behaviour at ambient temperature. The observations in this study indicate that lack of ductility is not a concern for cold-formed steels considered here at elevated temperatures.

3.5 Comparison of Yield Strength and Elastic Modulus Reduction Factors with those Available in Cold-formed Steel Structures Design Standards

The reduction factors of yield strength and elastic modulus were compared with those specified in BS5950 Part 8 [1] and Eurocode 3 Part 1.2 [2]. BS5950 Part 8 [1] provides the yield strength reduction factors at total strain levels of 0.5%, 1.5% and 2.0% whereas Eurocode provides them based on 0.2% proof stress. BS5950 Part 8 [1] reduction factors based on 0.5% total strain level were used in the comparison since the 0.2% proof stress and the stress corresponding to 0.5% of total strain were found to be very close to each other (see Table 2). Figure 10 (a) shows the comparison of yield strength reduction factors for both low and high strength steels from this research with corresponding values given in BS5950 Part 8 [1] and Eurocode 3 Part 1.2 [2].

A significant difference up to 20% can be seen between the yield strength reduction factors obtained from this research and the current cold-formed steel design standards for temperatures beyond 200$^{\text{o}}$C. It appears that the reduction factors beyond 200$^{\text{o}}$C given in both Eurocode 3 Part 1.2 [2] and BS5950 Part 8 [1] are unconservative while at 200$^{\text{o}}$C and 300$^{\text{o}}$C both design codes under-predict them for G450 steels. The yield strength reduction factors obtained from this research were dependant on the grade of steel. However, the design standards provide the same reduction factors for all the steel grades.

The elastic modulus reduction factors obtained from this study are compared with those in Eurocode 3 Part 1.2 [2] in Figure 10 (b), which shows that Eurocode 3 Part 1.2 [2] overestimates these factors for both low and high strength steels at all the temperatures except 700$^{\text{o}}$C, ie. not safer to use. The maximum difference is about 23% and occurs at 500$^{\text{o}}$C. BS5950 Part 8 [1] does not provide any reduction factors for elastic modulus.

3.6 Comparison of Yield Strength and Elastic Modulus Results with Available Research Results

Outinen [4] provided the reduction factors for both yield strength and elastic modulus of 2 mm thick cold-rolled hot dip zinc coated structural steel S350GD+Z (Z35) while Mecozzi and

Zhao [5] proposed suitable reduction factors for 0.6 mm S280 and 1.2 mm and 2.5 mm S350 cold-formed steels. Chen and Young [6] provided a unified equation for the yield strength reduction factors of 1.9 mm Grade 450 and 1.0 mm G550 cold-formed steels. They also proposed a unified equation for the elastic modulus reduction factor of 1.9 mm Grade 450 steel. A series of tensile coupon tests was also undertaken by QUT researchers [8-10]. Ranawaka and Mahendran [8] developed predictive equations for the reduction factors of yield strength and elastic modulus for 0.6 mm, 0.8 mm and 0.95 mm of Grade 550 and 250 steels. Kolarkar [10] determined the reduction factors for 1.15 mm G500 cold-formed steels while Bandula Heva [9] gave these factors for 0.42 mm G550 cold-formed steels.

The yield strength reduction factors are compared with those given by other researchers in Figure 11 (a). Mecozzi and Zhao's [5] yield strength reduction factors based on 0.2% proof stress for S280 and S350 steels do not agree with the test results of this study for G250 or G450 steels. Their proposed reduction factors for S280 steels are overconservative in the temperature range of 200°C to 500°C in comparison to the results of this study for G250 steels. Their proposed reduction factors for S350 steels are overconservative for high strength steels in the temperature range of 200°C to 400°C while they are unconservative in the temperature range of 500°C to 700°C. Chen and Young's [6] predictions for 1.9 mm G450 steel are in closer agreement up to 300°C. Thereafter their predictions are unconservative up to 600°C when compared with the results from this study although they are for the same steel grade and thickness. There is about 20% difference between the results from this research and Chen and Young's [6] predictions for Grade 550 steel at 450°C. Outinen's [4] results are too unconservative beyond 300°C for high strength steels while there is a closer agreement up to 300°C. Therefore neither the predictive equations of Chen and Young [6] for Grade 450 and Grade 550 steels nor the results of Outinen [4] for S350 steels and Mecozzi and Zhao [5] for S280 and S350 steels are accurate for 1.55 mm and 1.95 mm Grade 250 and 1.50 mm and 1.90 mm G450 cold-formed steels considered in this study.

Ranawaka and Mahendran [8] observed a significant difference in the reduction of yield strength at elevated temperatures depending on the steel grade, which was confirmed by the results of this study. This is also confirmed by the results of Mecozzi and Zhao [5] for the two different steel grades they tested. Ranawaka and Mahendran [8] proposed separate equations for both low and high strength steels (G250 and G550) of thickness less than 1 mm. Figure 11

(a) shows that their proposed reduction factors agree reasonably well with the results from this research for thicker low and higher strength steels (G250 and G450). However, further comparison was made with the results of Kolarkar [10] and Bandula Heva [9] as shown in Figure 12 to improve the accuracy of Ranawaka and Mahendran's [8] predictive equations. Figure 12 (a) clearly shows that the results from this research for Grade 250 steel are in good agreement with the reduction factors obtained using the proposed equations for G250 steel by Ranawaka and Mahendran [8]. However, Ranawaka and Mahendran's [8] equation is slightly overconservative in the temperature range of 200°C to 400°C. The reduction factors obtained from this study for Grade 450 steel are also in good agreement with the results of Kolarkar [10], Bandula Heva [9] and the predictive equation of Ranawaka and Mahendran [8] for Grade 550 cold-formed steels. However, in the temperature range of 400°C to 600°C, Ranawaka and Mahendran's [8] reduction factors for G550 steel are slightly unconservative for G450 steel. It is noted that Ranawaka and Mahendran's [8] proposed equations for G550 steel are also slightly unconservative in the same temperature range based on the results of Kolarkar [10] for G500 steels, and Bandula Heva's [9] results and the results of this study for G450 steels.

Elastic modulus reduction factors are compared with those given by other researchers in Figure 11 (b). The results from Kolarkar [10] and Bandula Heva [9] are closer to the results from this study except at 400°C in the case of Kolarkar's [10] results. Further, the results of Outinen [4] overestimate the elastic modulus in most cases except at 700°C. It is also noted that Ranawaka and Mahendran's [8] predictive equations overestimate the results at 100°C and beyond 450°C. It appears that Chen and Young's results accurately predict the reduction factors from 100°C to 300°C while their results overestimate the reduction factors between 400°C to 500°C. Mecozzi and Zhao's [5] results for S280 steel are overconservative for the temperature range of 300°C to 700°C while their results for S350 steel are not accurate, mostly at 100°C and 400°C. Therefore most of the proposed equations cannot be used to calculate the elastic modulus reduction factors for 1.55 mm and 1.95 mm G250 and 1.50 mm and 1.90 mm G450 cold-formed steels considered in this study, especially at high temperatures.

3.7 Stress-Strain Model

Stress-strain curves of G450 steels at ambient and elevated temperatures are of the gradual yielding type while they are the same for G250 steels at elevated temperatures beyond 200°C. Ramberg and Osgood [14] proposed a simple formula to describe the non-linear stress-strain curve at ambient temperature. Olawale and Plank [15] and Outinen [4] proposed stress-strain models for hot-rolled steels at elevated temperatures based on Ramberg and Osgood's [14] model. Lee et al. [7] and Ranawaka and Mahendran [8] also proposed stress-strain models for cold-formed steels based on Ramberg and Osgood's model while Chen and Young [6] developed a model for cold-formed steels based on the model developed by Mirambell and Real [16] and Rasmussen [17] for stainless steel at room temperature, which is also based on Ramberg and Osgood [14].

Ranawaka and Mahendran [8] stated that the stress-strain model proposed by Lee et al. [7] is not suitable to predict the stress-strain model of light-gauge cold-formed steels at elevated temperatures. Chen and Young [6] showed that the proposed models by Olawale and Plank [15], Outinen [4] and Lee et al. [7] do not accurately predict the stress-strain curves of cold-formed steels for temperatures in the range of 22°C to 660°C. Therefore the accuracy of the models proposed by Ranawaka and Mahendran [8] and Chen and Young [6] was investigated using the test results obtained from this research to determine the most suitable stress-strain model for cold-formed steels at elevated temperatures.

In Figures 13 (a) and (b), the predicted stress-strain curves based on Ranawaka and Mahendran [8] were compared against the stress-strain curves obtained in this study at selected temperatures for low and high strength cold-formed steels, respectively. The comparison was also made between the proposed stress-strain curves by Chen and Young [6] for high strength steels with the results of this study for low and high strength steels in Figure 14 (a) and (b), respectively. It can be clearly seen that the stress-strain curves predicted by Ranawaka and Mahendran [8] for G450 steel are in good agreement with the test results. Chen and Young's [6] predicted stress-strain curves are in good agreement with the test results of G450 steel up to about 0.5% strain. It can be seen that there is a significant difference thereafter at temperatures 300°C, 400°C and 500°C. Therefore it is concluded that the stress-strain curve model proposed by Ranawaka and Mahendran [8] for high strength steel is more accurate for the cold-formed steels considered in this study.

It appears that there is a good agreement in the elastic region of the stress-strain curves obtained from Ranawaka and Mahendran [8] for G250 steel. However it is noted that the stress-strain model does not accurately predict the stresses in the plastic strain range, especially at 400°C and 500°C. The same observation is also made with Chen and Young's predictions. However, the stress-strain curves obtained from Ranawaka and Mahendran's [8] equations are closer to the stress-strain curves obtained here.

4 Predictive Equations for Mechanical Properties

4.1 Yield Strength

Many researchers proposed suitable equations for the yield strength reduction factors of cold-formed steels as a function of temperature [4-8]. Comparison of the yield strength results obtained from this research and the predicted values from these equations showed that they were unable to predict the yield strength reduction factors of 1.55 mm and 1.95 mm G250 and 1.50 mm and 1.90 mm G450 cold-formed steels at elevated temperatures accurately except Ranawaka and Mahendran's [8] equations. Although Ranawaka and Mahendran's equations predict the yield strength reduction factors of cold-formed steels reasonably well, certain modifications were identified as necessary. With the availability of accurate yield strength reduction factors of many different steel grades (G250, G450, G500 and G550) and thicknesses (0.42 to 1.95mm) from other QUT studies, it was considered important to develop predictive equations that are suitable for all the commonly used cold-formed steels in Australia. Therefore new predictive equations were proposed as follows based on the 0.2% proof stress method and all the available QUT test results [8-10].

For low strength steels,

$$20 \leq T \leq 200^o C \qquad \frac{f_{y,T}}{f_{y,20}} = -0.0005T + 1.01 \qquad (1a)$$

$$200 < T \leq 800^o C \qquad \frac{f_{y,T}}{f_{y,20}} = 25\left(1.16 - T^{0.022}\right) \qquad (1b)$$

Equations 1 (a) and (b) present the proposed equations for the reduction factors ($f_{y,T}/f_{y,20}$) of low strength steels (G250), where $f_{y,T}$ and $f_{y,20}$ are the 0.2% proof stresses at elevated and ambient temperatures, respectively, and T is the temperature. The predictions from Equations 1 (a) and (b) are compared with the test results from this study in Figure 15 (a) and with all the test results from QUT research in Figure 15 (b). These figures show that there is good agreement between the proposed equations and the test results from QUT. Therefore it is recommended to use the modified equations 1 (a) and (b) to determine the yield strength reduction factors of all the low strength cold-formed steels at elevated temperatures.

Similarly a new set of equations was developed to determine the yield strength reduction factors of high strength steels (G450, G500 and G550) by considering all the test results obtained by QUT researchers including those from this study. The reduction factors of high strength steels show three main regions: two nonlinear regions (20 – 300°C and 300 – 600°C) and one linear region (600 – 800°C). Three equations were therefore developed to represent them as the first option. Equations 2 (a) to (c) present the proposed equations for the yield strength reduction factors ($f_{y,T}/f_{y,20}$) of high strength steels.

For high strength steels (Option 1),

$$20 \leq T < 300^{o}C \qquad \frac{f_{y,T}}{f_{y,20}} = \left\{ 1 - \frac{(T-20)^{4.56}}{1x10^{10}T} \right\} \qquad (2a)$$

$$300 \leq T < 600^{o}C \qquad \frac{f_{y,T}}{f_{y,20}} = \left\{ 0.95 - \frac{(T-300)^{1.45}}{7.76T} \right\} \qquad (2b)$$

$$600 \leq T \leq 800^{o}C \qquad \frac{f_{y,T}}{f_{y,20}} = -0.0004T + 0.35 \qquad (2c)$$

In Figures 16 (a) and (b), the predictions from Equations 2 (a) to (c) are compared with the test results from this research and all the test results from QUT research, respectively. As shown in Figure 16 (a) there is good agreement between the test results of this study and the proposed equations. Figure 16 (b) shows that a good agreement also exists between the results of other QUT studies and the proposed equations. Therefore it is recommended to use the

modified equations 2 (a) to (c) to determine the yield strength reduction factors of all the high strength steels (G450, G500 and G550) at elevated temperatures.

In the second option linear equations were proposed for the 20°C to 300°C and 600°C to 800°C temperature ranges while a non-linear equation was proposed for the 300°C to 600°C range (Equations 3a-c). Figures 17 (a) and (b) show that QUT test results are in good agreement, and therefore Equations 3 (a) to (c) can also be used in predicting the yield strength reduction factors of high strength steels.

For high strength steels (Option 2),

$20 \leq T < 300^{o}C$ $\qquad\qquad$ $\dfrac{f_{y,T}}{f_{y,20}} = -0.000179T + 1.00358$ $\qquad\qquad$ (3a)

$300 \leq T < 600^{o}C$ $\qquad\qquad$ $\dfrac{f_{y,T}}{f_{y,20}} = \left\{ 0.95 - \dfrac{(T-300)^{1.45}}{7.76T} \right\}$ $\qquad\qquad$ (3b)

$600 \leq T \leq 800^{o}C$ $\qquad\qquad$ $\dfrac{f_{y,T}}{f_{y,20}} = -0.0004T + 0.35$ $\qquad\qquad$ (3c)

As an alternative to Equations 2 and 3, three simple linear equations were also developed for the three regions: 20°C – 300°C, 300°C – 600°C and 600°C – 800°C as given in Equations 4(a) to (c). Figures 18 (a) and (b) show a good agreement between the predicted values and the test results from QUT research. Equations 1(a) to (c) provide the most accurate predictions of yield strengths of high strength steels at elevated temperatures. However, Equations 4(a) to (c) are recommended if simpler predictive equations are needed.

For high strength steels (Option 3),

$20 \leq T < 300^{o}C$ $\qquad\qquad$ $\dfrac{f_{y,T}}{f_{y,20}} = -0.000179T + 1.00358$ $\qquad\qquad$ (4a)

$300 \leq T < 600^{o}C$ $\qquad\qquad$ $\dfrac{f_{y,T}}{f_{y,20}} = -0.0028T + 1.79$ $\qquad\qquad$ (4b)

$600 \leq T \leq 800^{o}C$ $\qquad\qquad$ $\dfrac{f_{y,T}}{f_{y,20}} = -0.0004T + 0.35$ $\qquad\qquad$ (4c)

4.2 Elastic modulus

Several researchers [4,6-8] have developed predictive equations for the elastic modulus reduction factors as a function of temperature. Since none of them accurately predicted the elastic modulus reduction factors, new empirical equations were developed. There are two main regions in which elastic modulus reduction factors vary linearly: 20°C-200°C and 200°C–800°C. Test results from this study showed that the influence of steel grade and thickness on the elastic modulus reduction factors is negligible. Hence neither steel thickness nor steel grade was included in developing the predictive equations. Two linear equations were developed for the two identified temperature regions to predict the elastic modulus reduction factors at elevated temperatures (Equation 5). Figures 19 (a) and (b) show that the test results from this study and past QUT research agree well with the above equations.

For low and high strength steels,

$$20 \leq T \leq 200^{o}C \qquad\qquad \frac{E_T}{E_{20}} = -0.000835T + 1.0167 \qquad\qquad (5a)$$

$$200 < T \leq 800^{o}C \qquad\qquad \frac{E_T}{E_{20}} = -0.00135T + 1.1201 \qquad\qquad (5b)$$

4.3 Stress-strain Curves

The stress-strain model at elevated temperature is usually based on the Ramberg-Osgood stress-strain model and is given by Equation 6 where ε_T is the strain corresponding to a given stress f_T at temperature (T), E_T and $f_{y,T}$ are elastic modulus and yield strength, respectively, and η_T and β are two parameters. Ranawaka and Mahendran [8] proposed β to be taken as 0.86 and two equations for η_T depending on the grade of steel as given in Equation 7 (a) and (b).

$$\varepsilon_T = \frac{f_T}{E_T} + \beta\left(\frac{f_{y,T}}{E_T}\right)\left(\frac{f_T}{f_{y,T}}\right)^{\eta_T} \qquad\qquad (6)$$

where,

For high strength steels (G550), $\qquad\qquad 20 \leq T \leq 800^{o}C$

$$\eta_T = -3.05 \times 10^{-7} T^3 + 0.0005 T^2 - 0.2615 T + 62.653 \qquad (7a)$$

$$\beta = 0.86$$

For low strength steels (G250), $\qquad 350 \le T \le 800^o C$

$$\eta_T = 0.000138 T^2 - 0.085468 T + 19.212 \qquad (7b)$$

$$\beta = 0.86$$

In the earlier sections, it was shown that the stress-strain curve model proposed by Ranawaka and Mahendran [8] accurately predicted the stress-strain curves of all the cold-formed high strength steels based on the results of this study. However, it was shown that their stress-strain model for low strength steels does not accurately predict the stresses in the plastic strain range, especially at 400°C and 500°C. Therefore the parameter β was modified to 1.5 in Equation 7(b) and used with Equation 6. The temperature range for which Equation 7(b) is valid is also changed based on the results of this research from $350 \le T \le 800^o C$ to $300 \le T \le 800^o C$. Figures 20 (a) and (b) show the comparison of stress-strain curves obtained from the modified equations and the experimental study for low strength steels. They show that these stress-strain curves are in good agreement. Therefore Equations 6 and 7 together with β equal to 0.86 for high strength steels and 1.5 for low strength steels are recommended for the determination of the stress-strain curves.

5 Conclusions

This paper has presented a detailed experimental study of the mechanical properties of cold-formed steels at elevated temperatures. The experimental study included tensile coupon tests conducted on 1.55 and 1.95 mm G250 and 1.50 and 1.90 mm G450 cold-formed steels at elevated temperatures in the range of 20 to 700°C. The yield and ultimate strengths, elastic modulus and the stress-strain curve were determined from these tests. The results showed that the steel grade had an influence on the yield strength of steel while there was no observable influence of steel thickness on the results. There was no clear relationship between the elastic modulus and the steel grade or thickness. Neither the current design standards nor the proposals by other researchers provided accurate reduction factors for both the yield strength and the elastic modulus of Australian cold-formed steels considered in this study. Therefore an improved set of predictive equations was developed for the yield strength and elastic

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modulus reduction factors of low and high strength Australian cold-formed steels at elevated temperatures based on all the test results obtained from past and present research at QUT. Ranawaka and Mahendran's [8] equations predict the stress-strain curves for high strength cold-formed steels reasonably well. However, an improvement was made to their equations in the case of low strength steels.

This paper has highlighted the lack of reliable predictive equations for the mechanical properties of cold-formed steels. Considerable differences in results appear to be due to the variation between cold-formed steels and the test methods used. A large amount of test data developed for typical low and high strength cold-formed steels in Australia have been used in this research to develop accurate predictive equations for their mechanical properties and stress-strain curves. It is considered that they are accurate for other cold-formed steels with similar characteristics.

6 Acknowledgements

7 References

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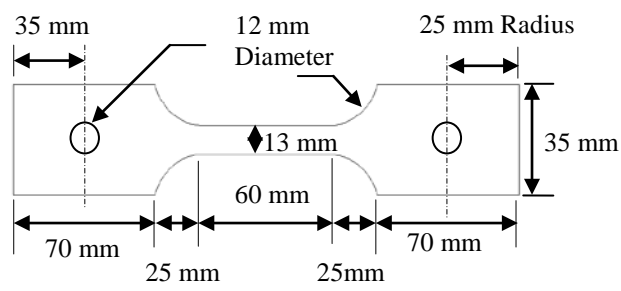
(a) Dimensions   (b) Test coupons

Figure 1: Tensile Test Coupons and Dimensions
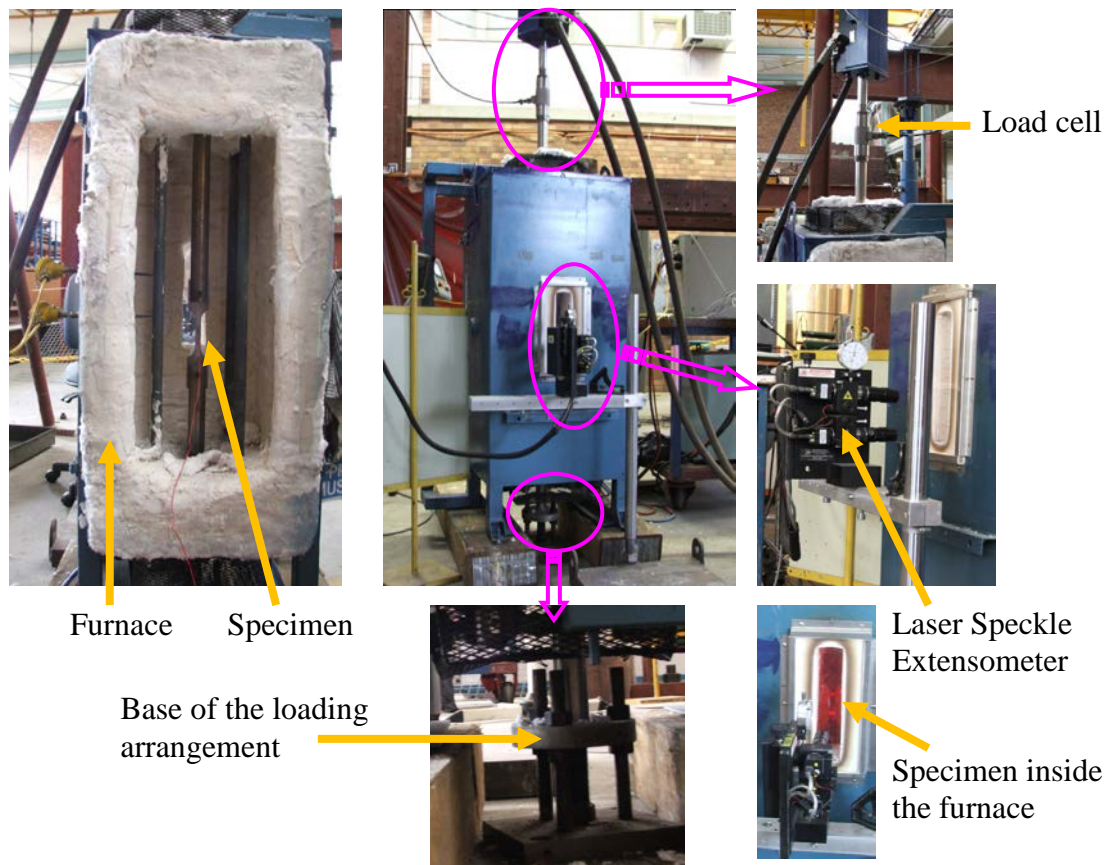
Figure 2: Details of Test Arrangement
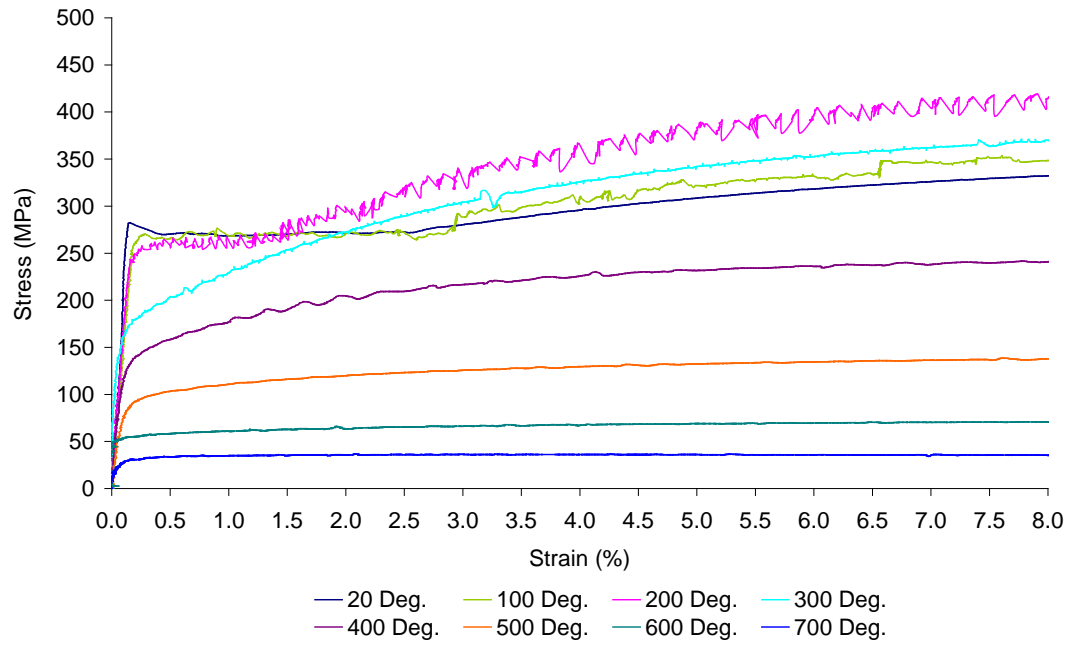
(a) 1.95 mm Grade 250
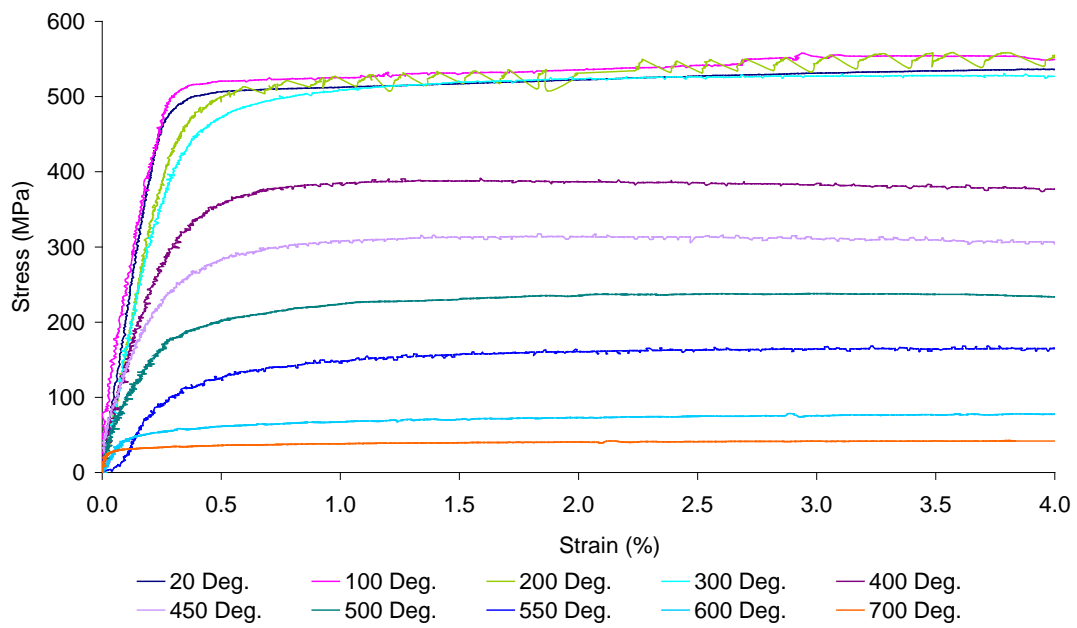
(b) 1.90 mm Grade 450

Figure 3: Stress-strain Curves at Different Temperatures
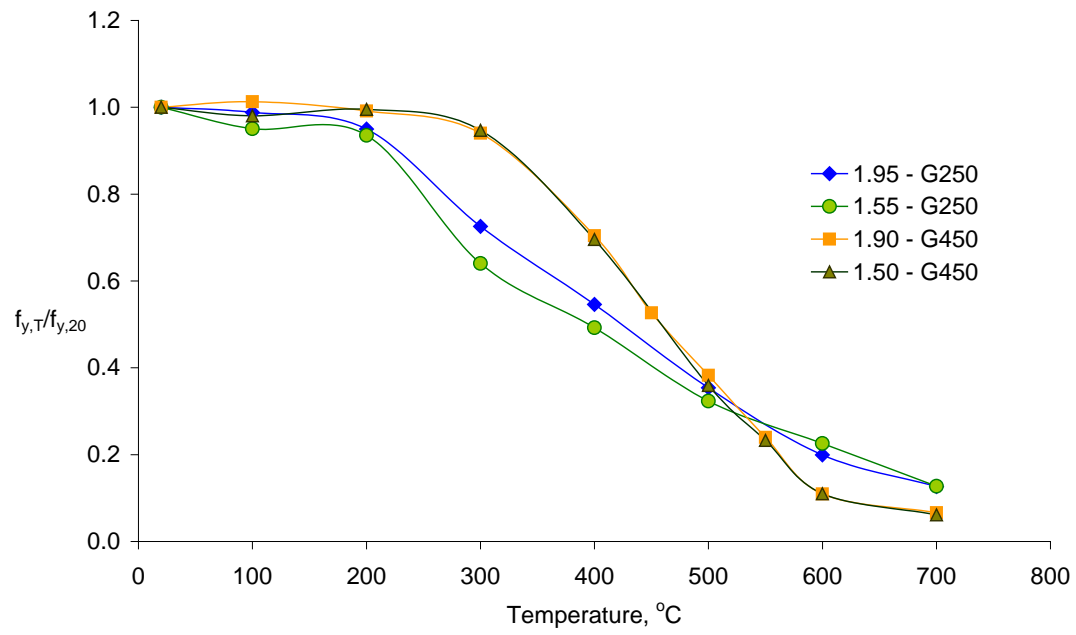
Figure 4: Yield Strength Reduction Factors versus Temperature for Different Steel Grades and Thicknesses
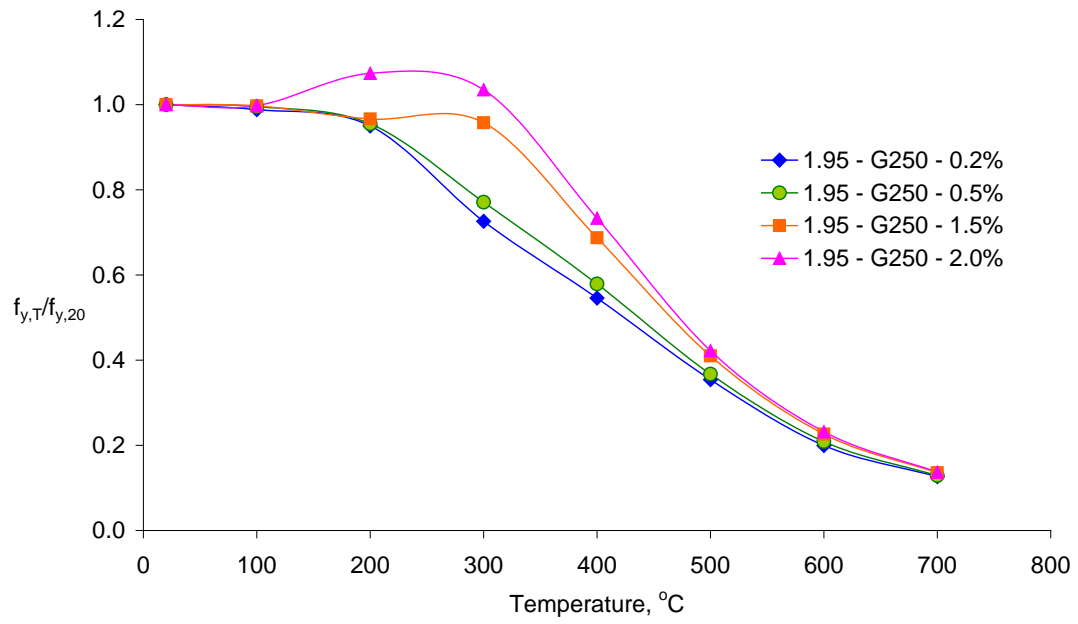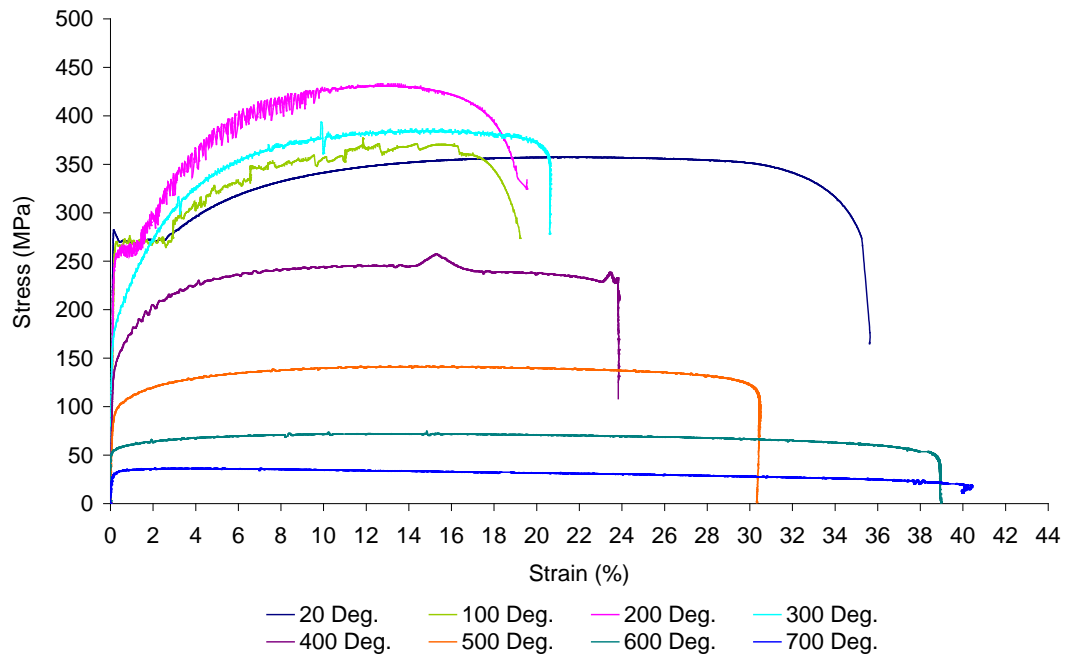
(a) 1.95 mm G250
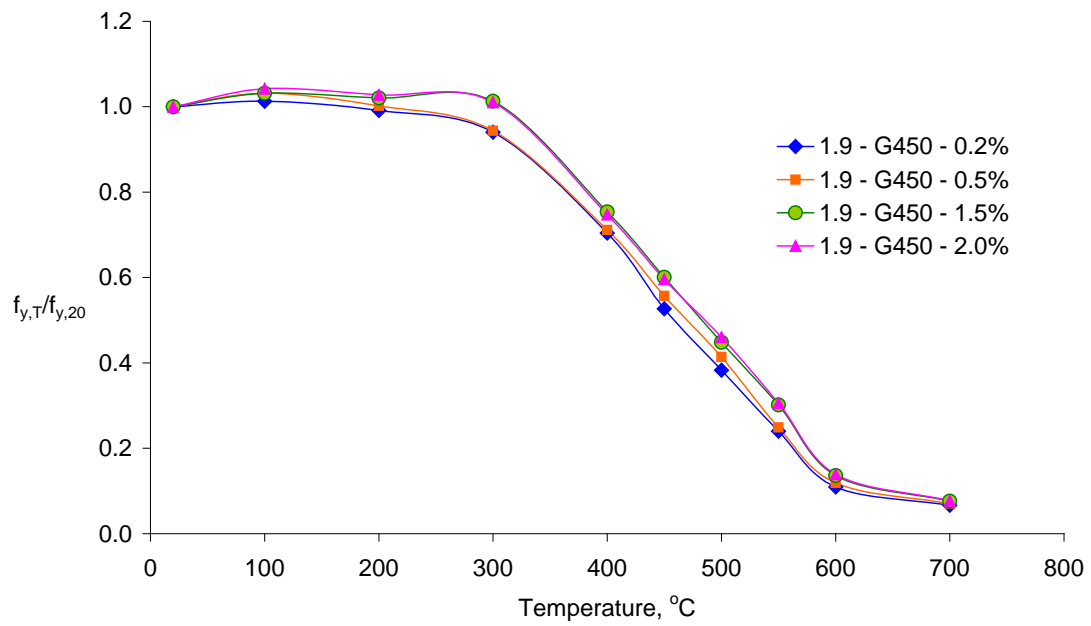
(b) 1.90 mm G450

Figure 5: Yield Strength Reduction Factor versus Temperature for Different Strain Levels
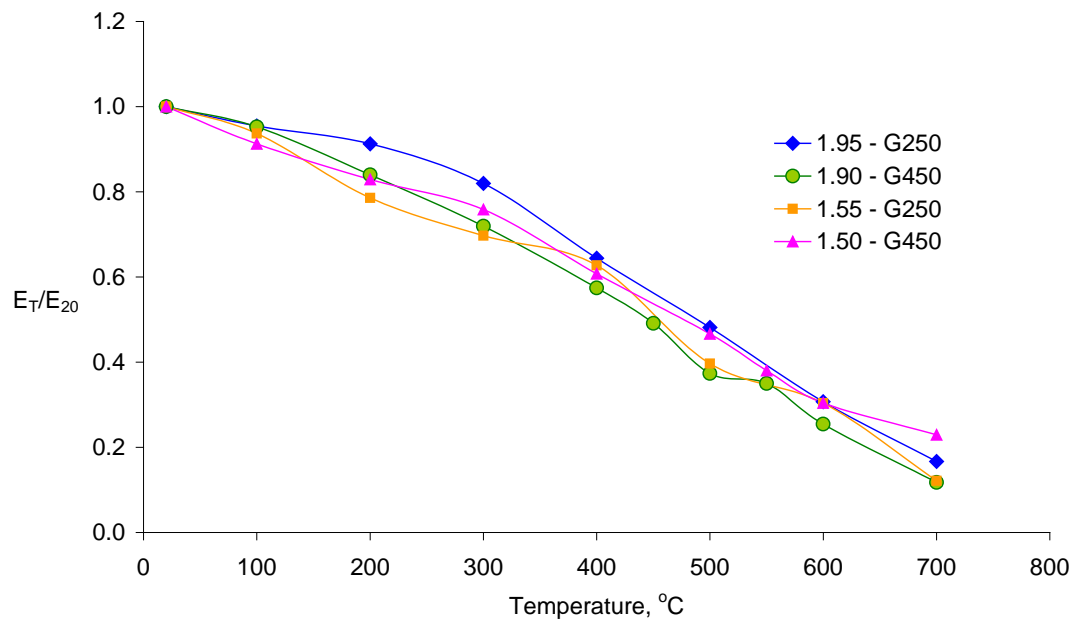
Figure 6: Elastic Modulus Reduction Factors versus Temperature for Different Steel Grades and Thicknesses
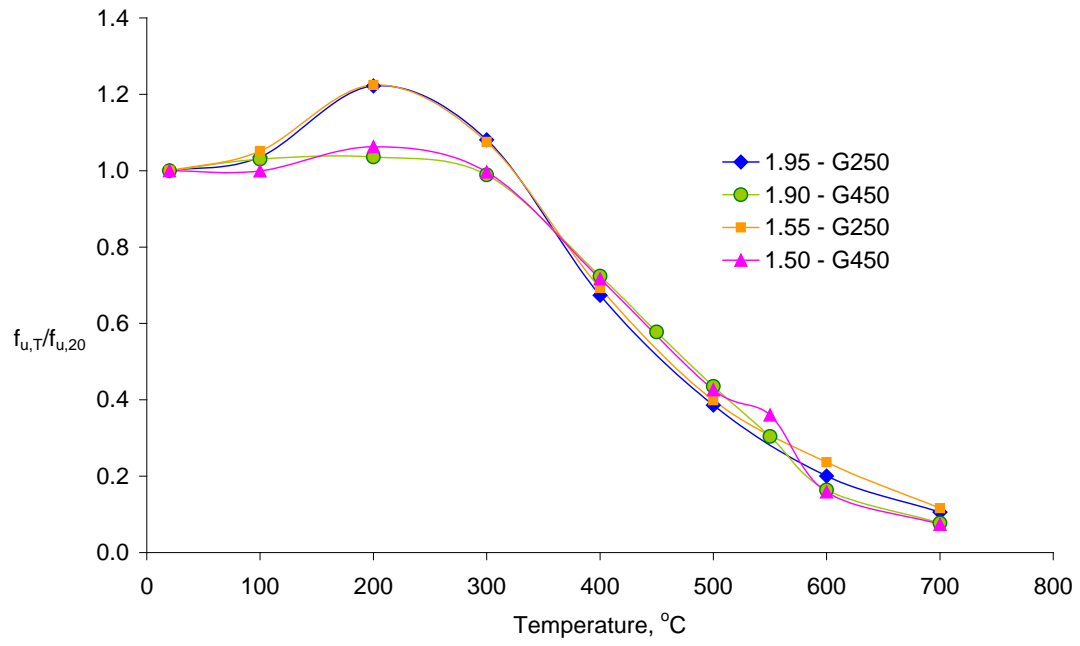
Figure 7: Ultimate Strength Reduction Factors versus Temperature for Different Steel Grades and Thickness

(a) 1.95 mm G250 steel
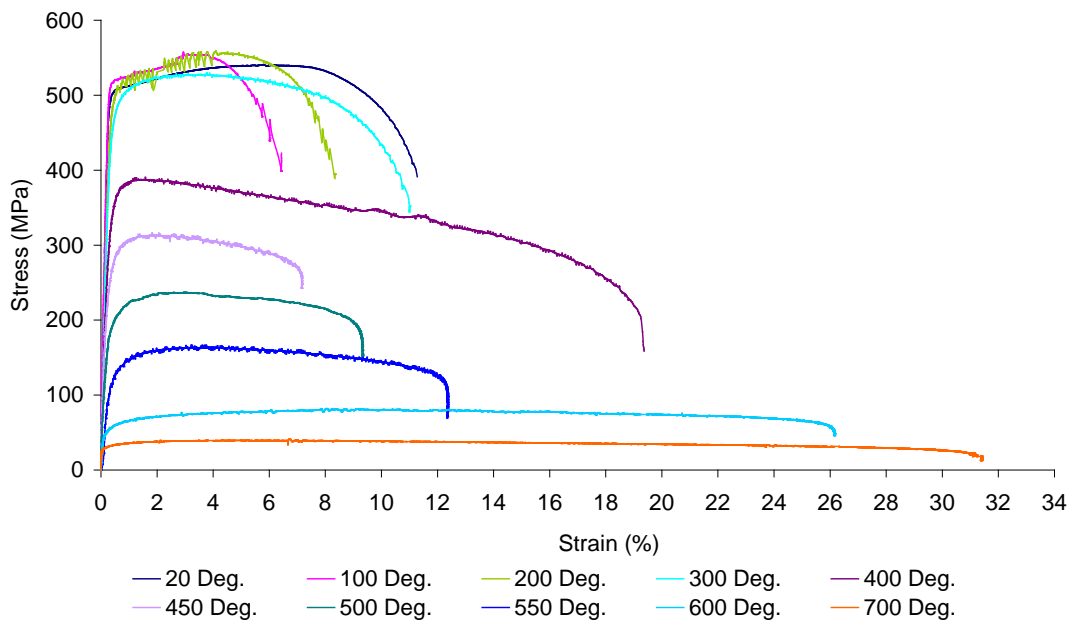
(b) 1.90 mm G450 steel

Figure 8: Stress-strain Curves at Various Temperatures
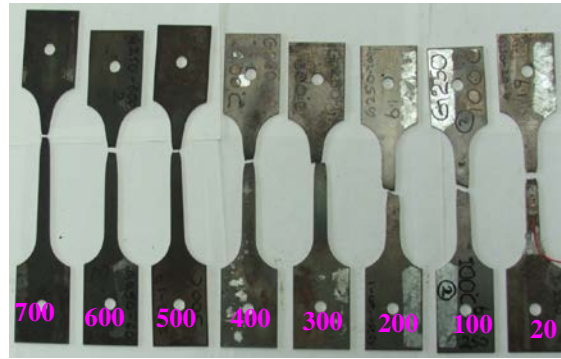
(a) 1.95 mm Grade 250 cold-formed steel
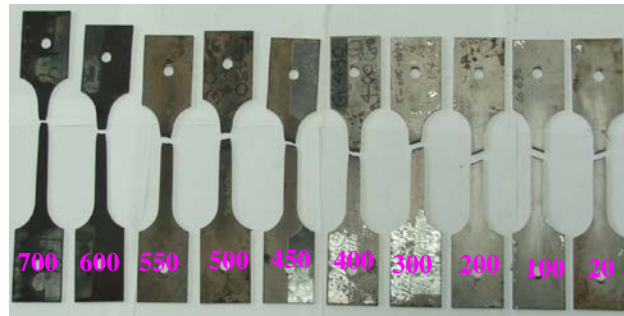
(b) 1.90 mm Grade 450 cold-formed steel

Figure 9: Failure Modes of Tensile Specimens at Elevated Temperatures
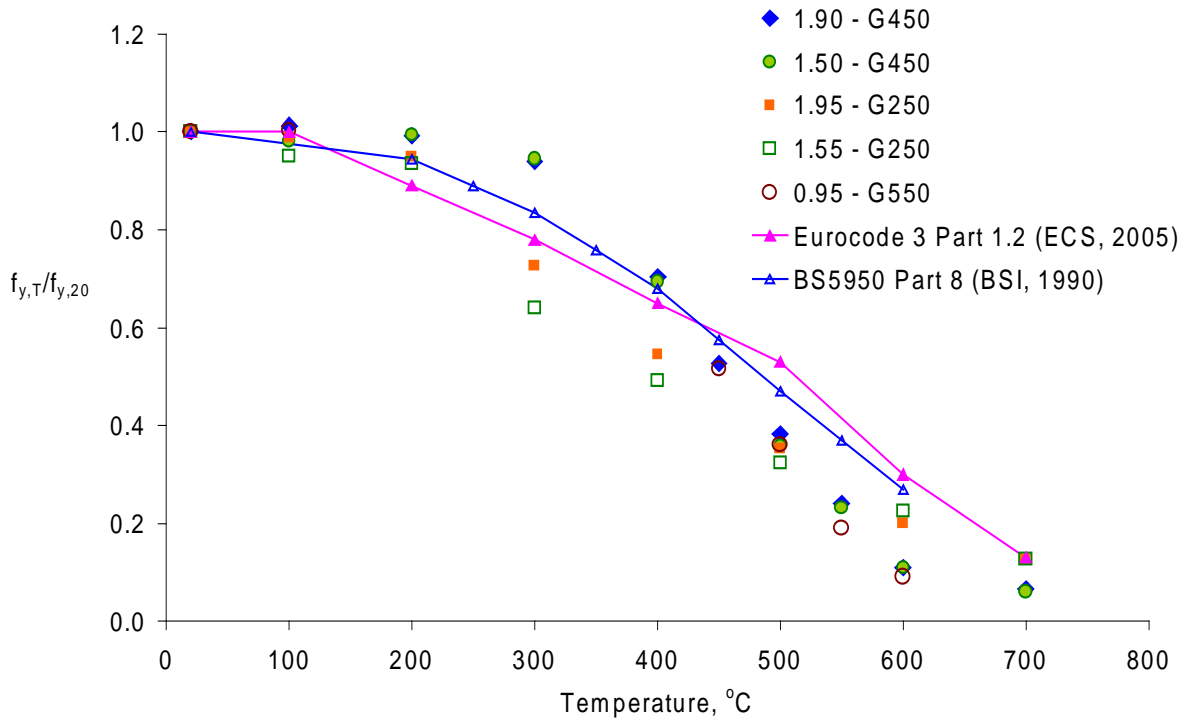
(a) Yield Strength
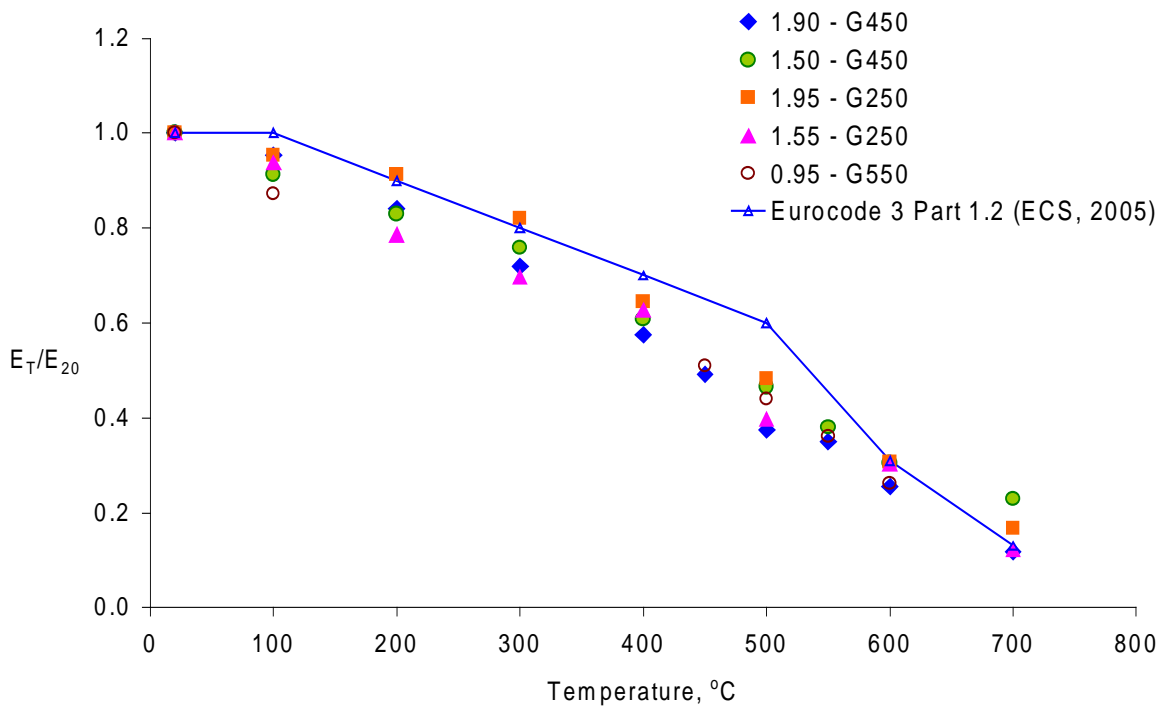
(b) Elastic Modulus

Figure 10: Comparison of Reduction Factors at Elevated Temperatures with Current Design Standards
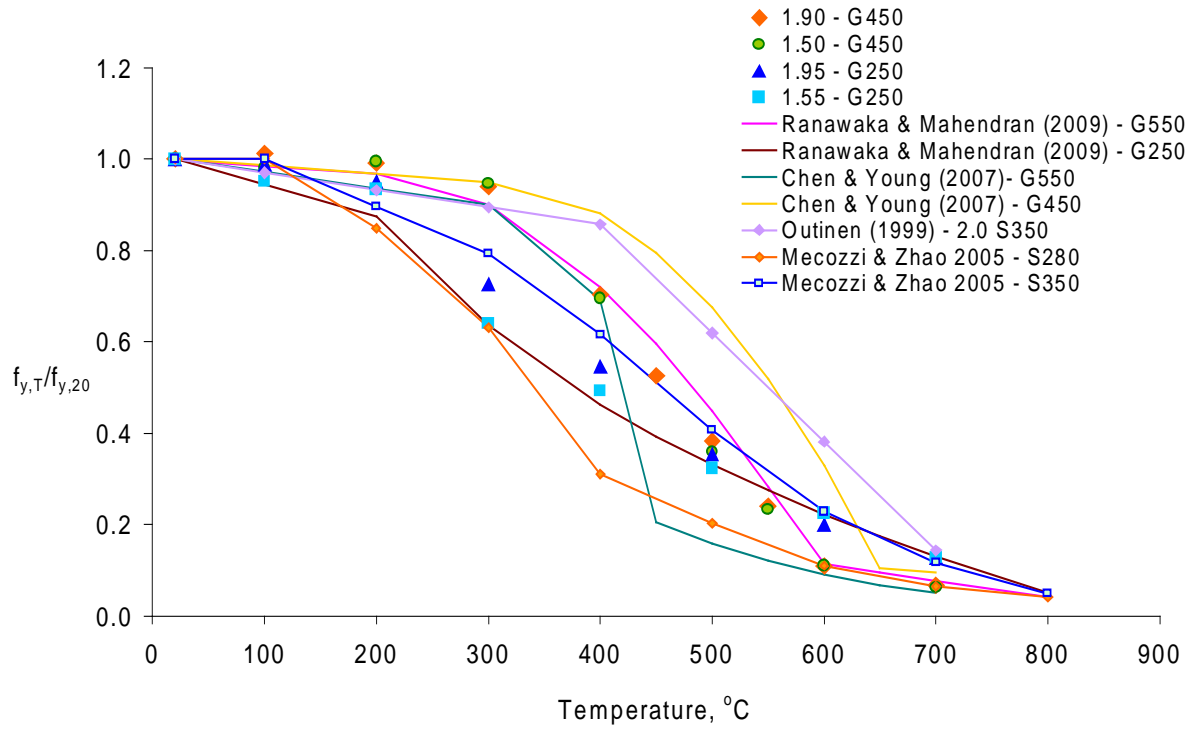
(a) Yield Strength
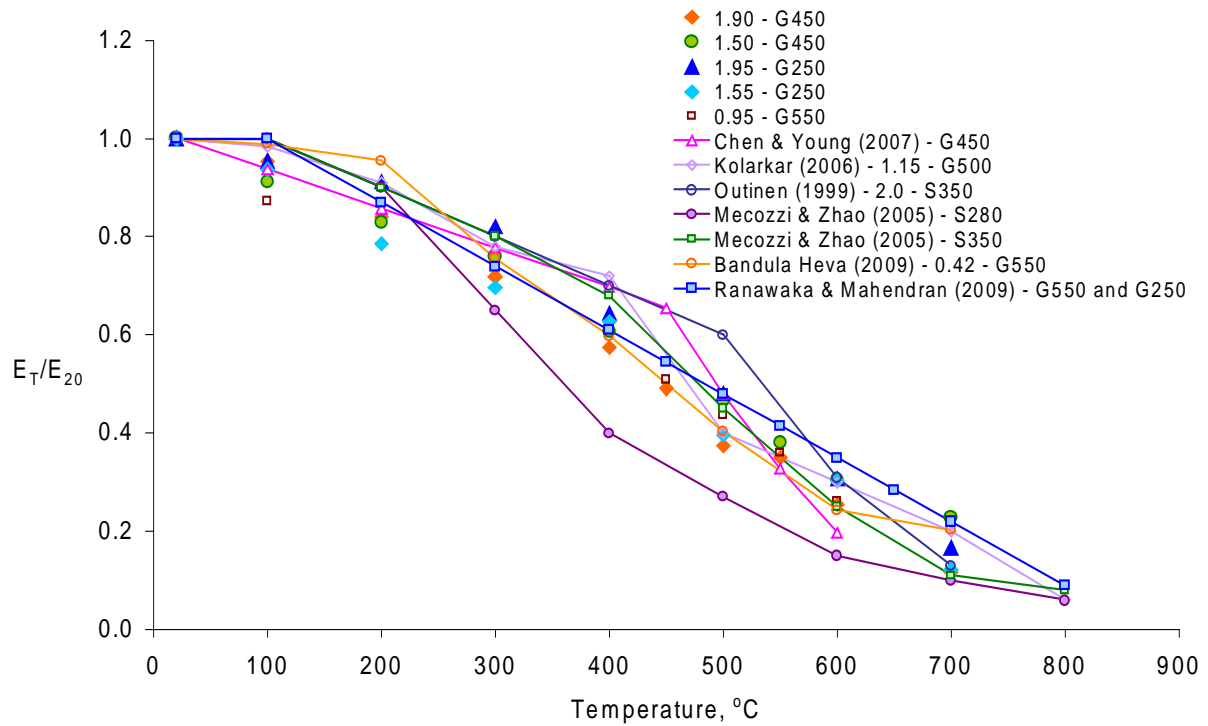
(b) Elastic Modulus

Figure 11: Comparison of Reduction Factors with those Obtained by Other Researchers
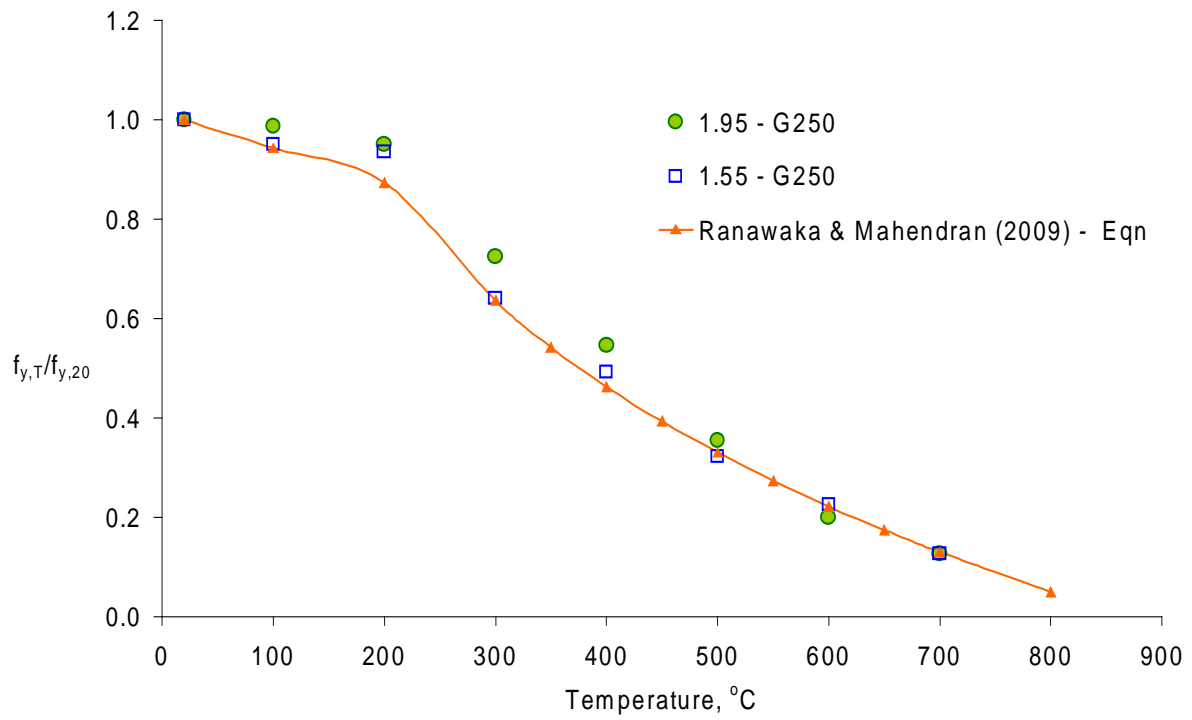
(a) Low strength steel
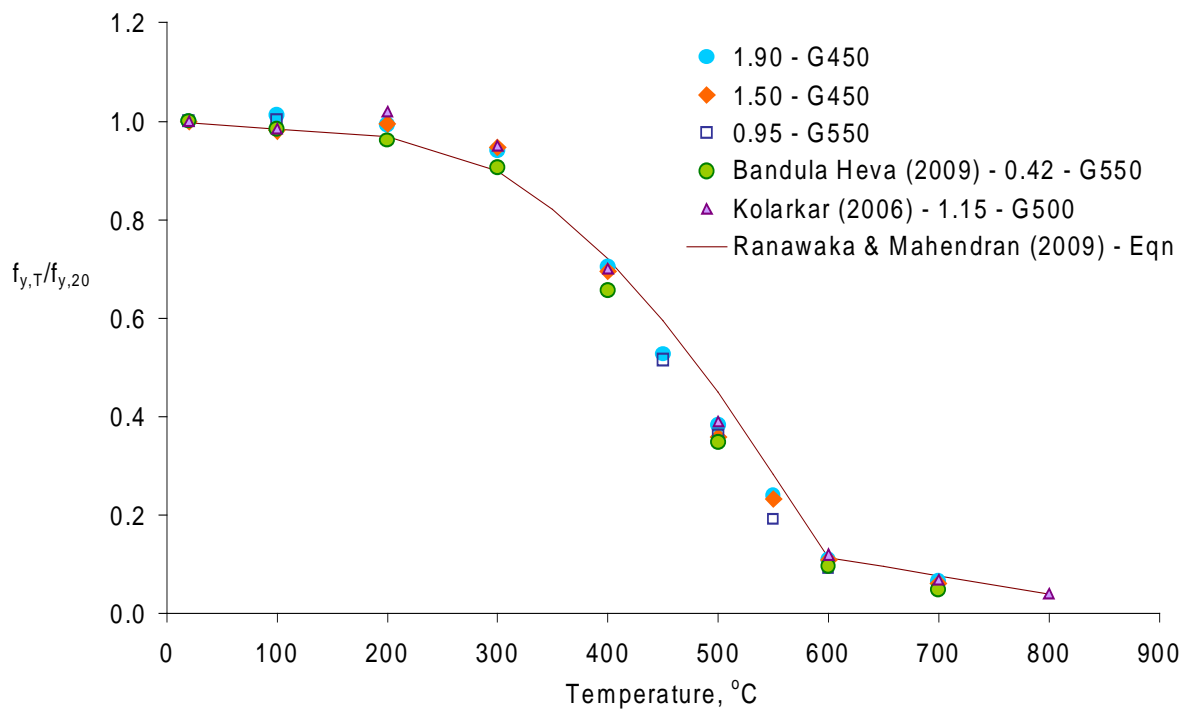
(b) High strength steel

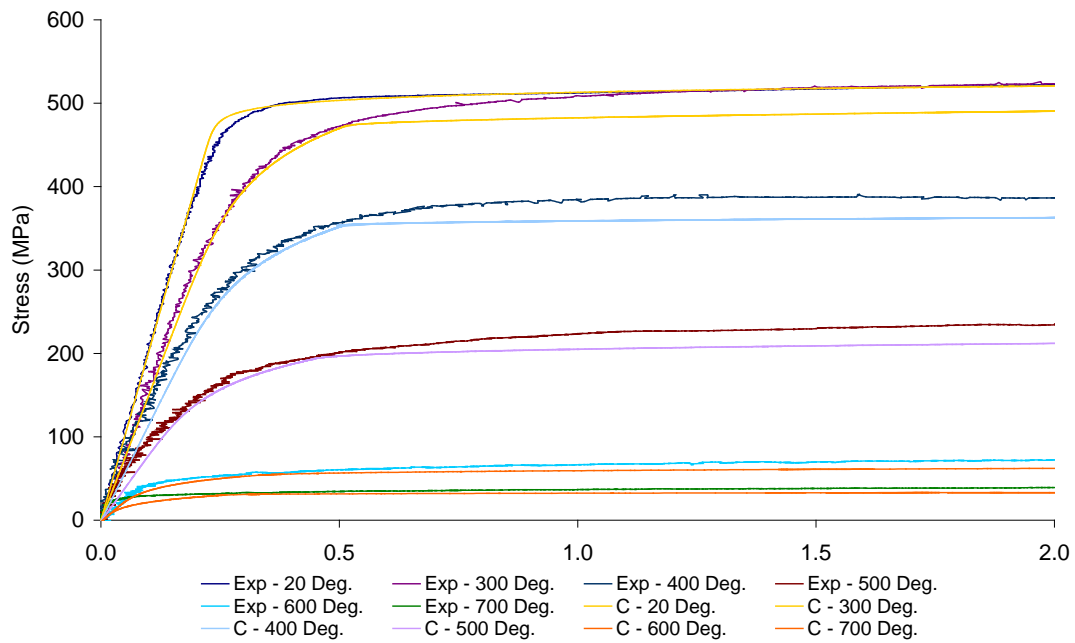**Figure 12: Comparison of Yield Strength Reduction Factors**
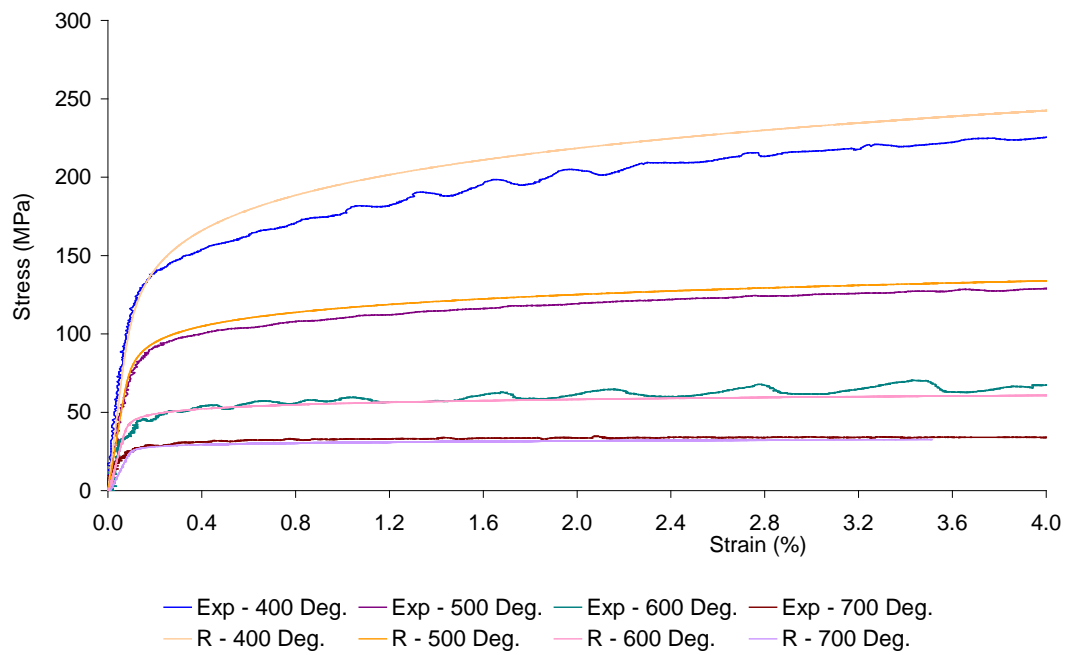
(a) 1.95 mm G250 steel
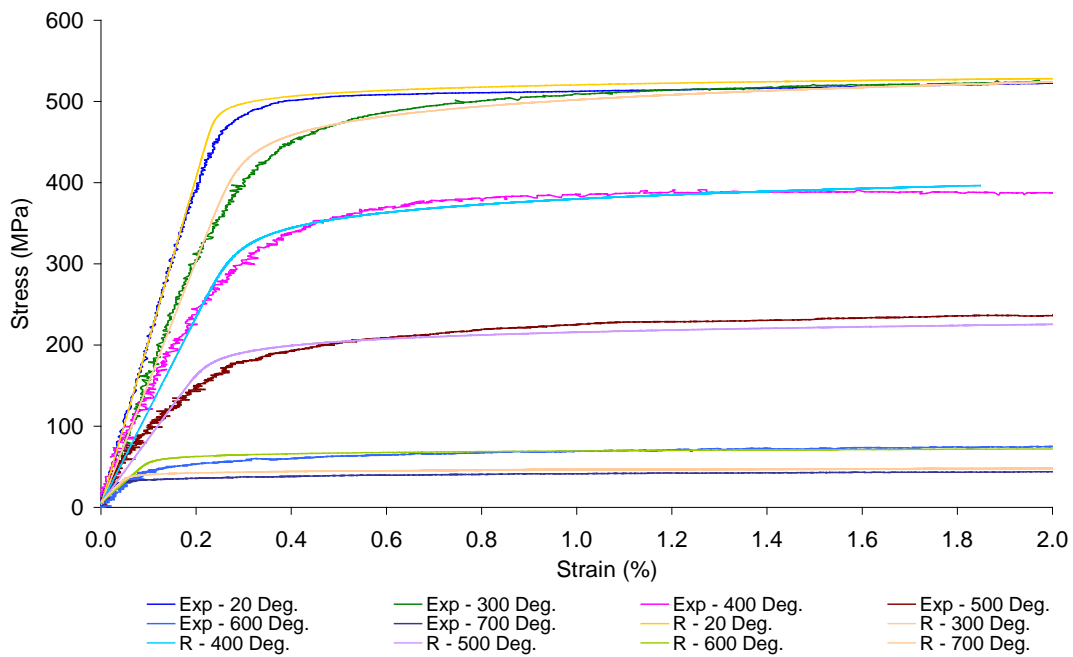
(b) 1.90 mm G450 steel

Note: R – Ranawaka and Mahendran [8]

Figure 13: Comparison of Predicted Stress-Strain Curves by Ranawaka and Mahendran [8] with Test Results
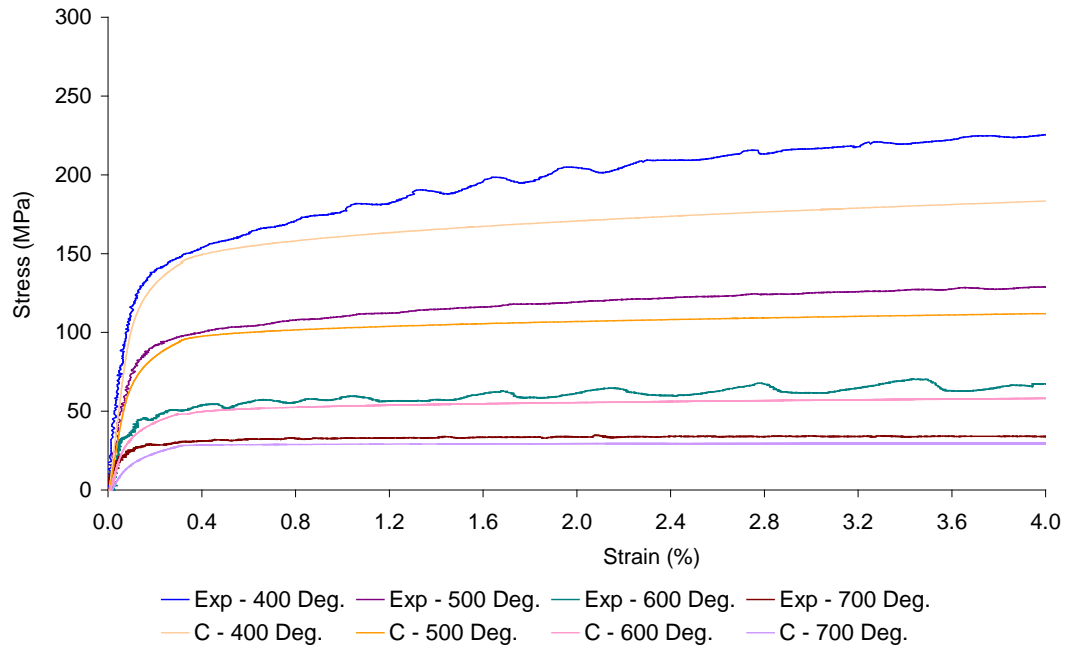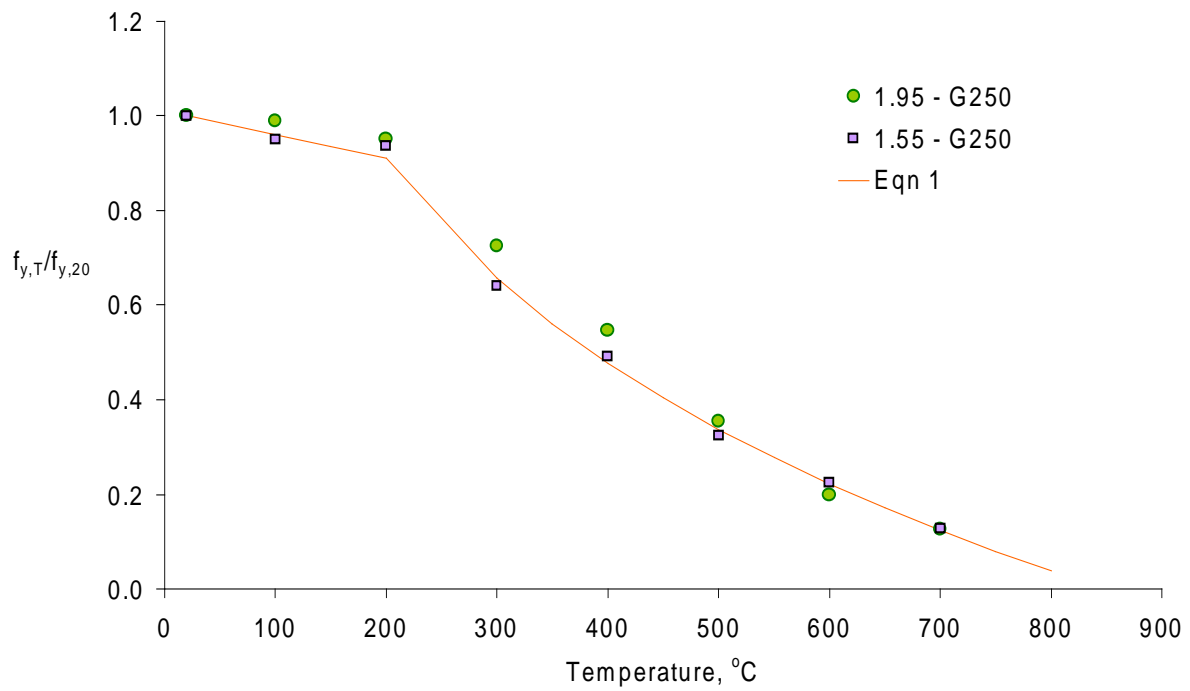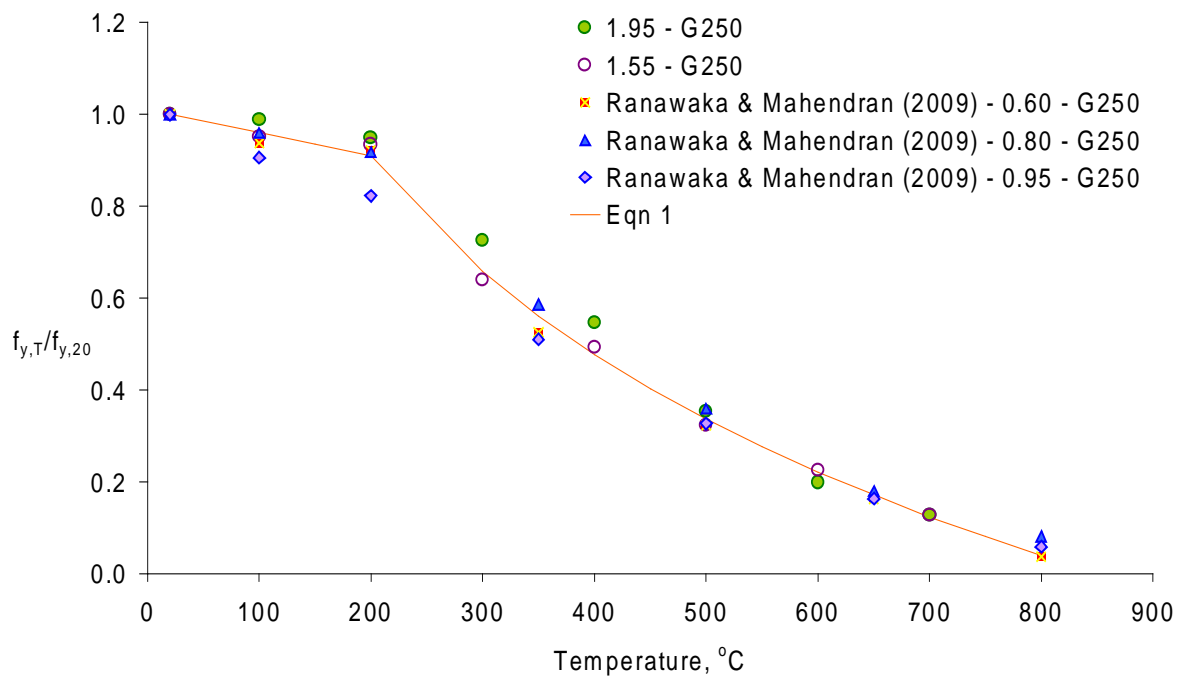
(a) 1.95 mm G250 steel

(b) 1.90 mm G450 steel

Note: C – Chen and Young [6]

Figure 14: Comparison of Predicted Stress-Strain Curves by Chen and Young [6] with Test Results
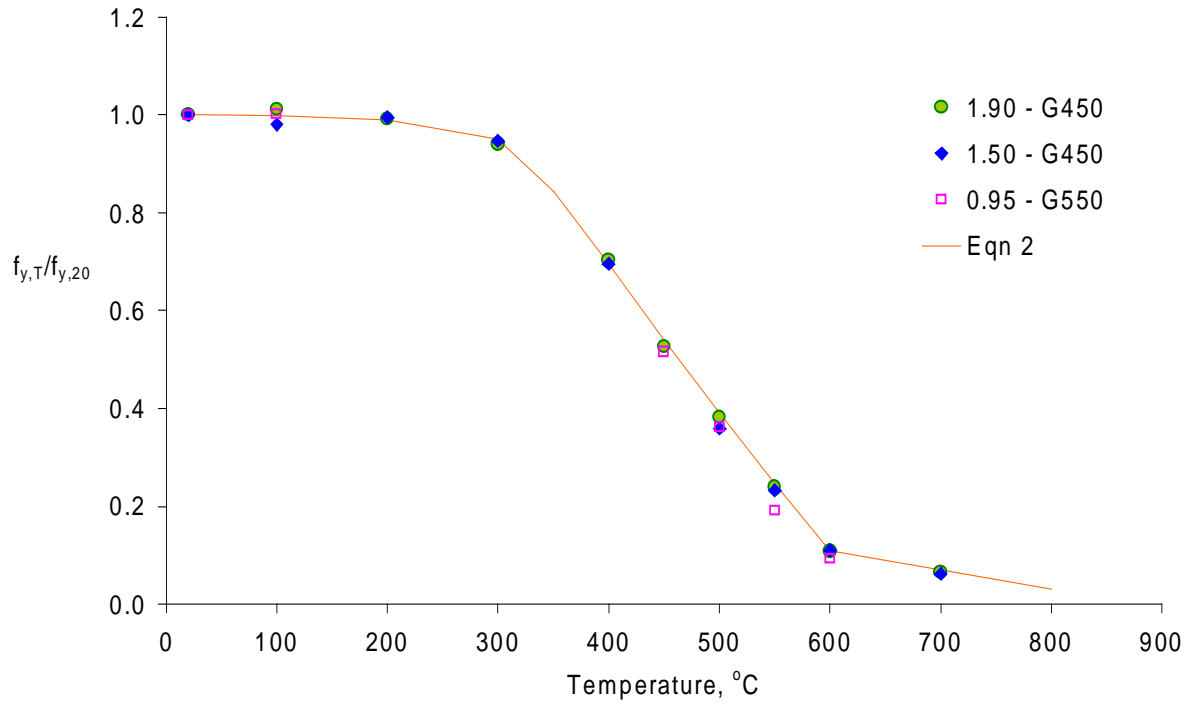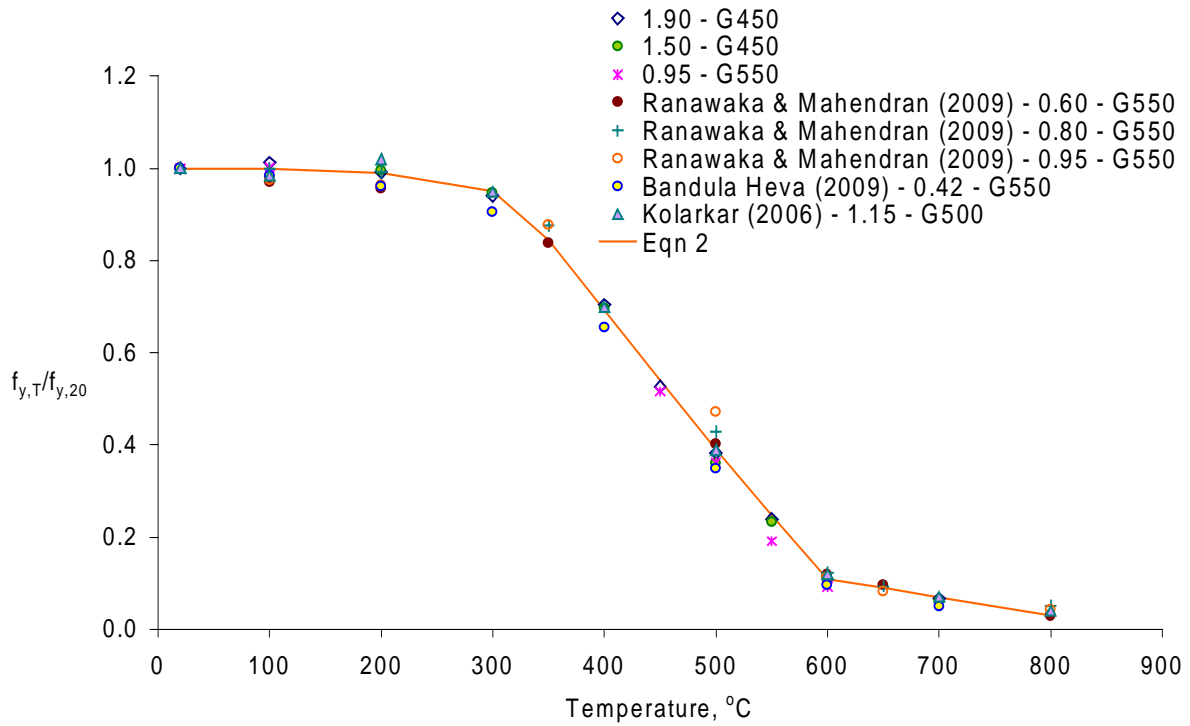
(a) Low strength steels - This research

(b) Low strength steels – QUT research

Figure 15: Comparison of Predicted Yield Strength Reduction Factors from Equation 1 with Test Results
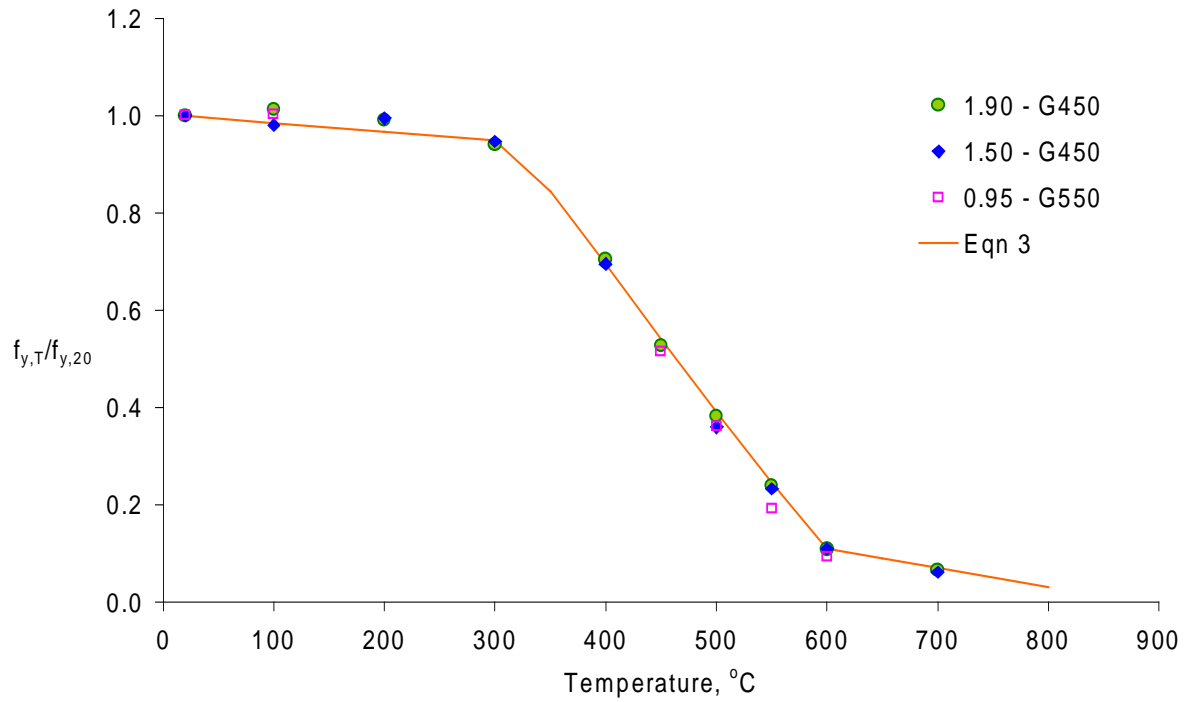
(a) This research

(b) QUT research

Figure 16: Comparison of Predicted Yield Strength Reduction Factors from Equation 2 with Test Results

(a) This research

(b) QUT research

Figure 17: Comparison of Predicted Yield Strength Reduction Factors from Equation 3 with Test Results
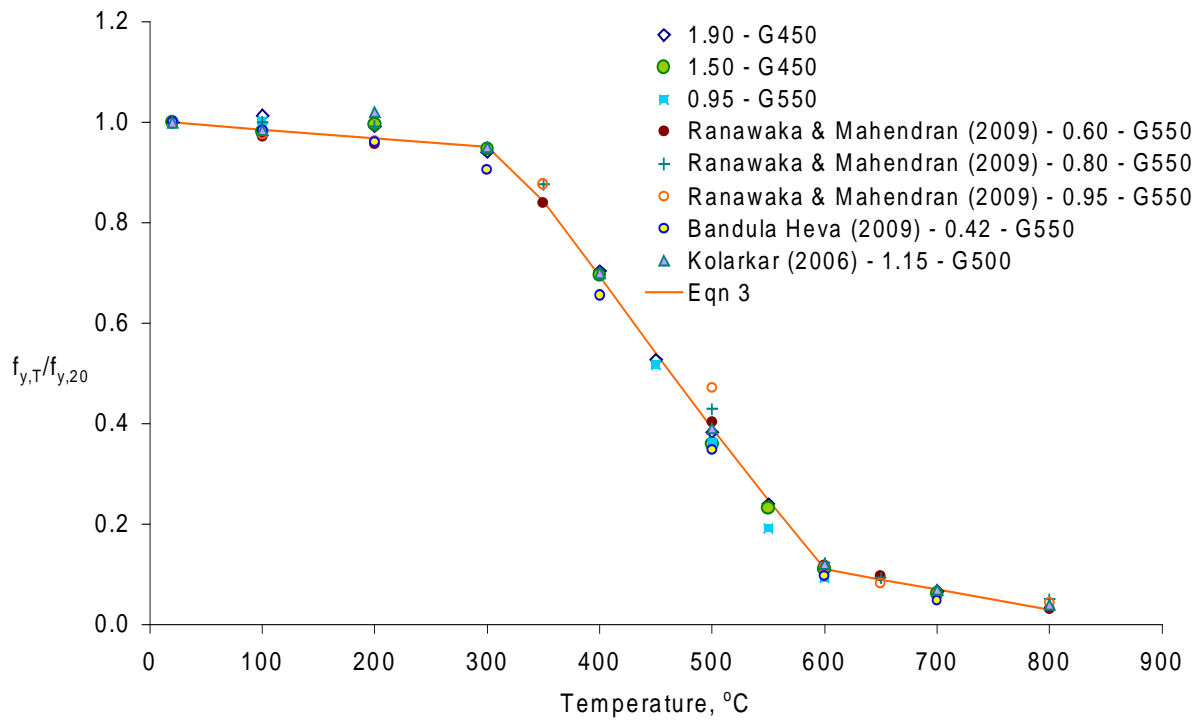
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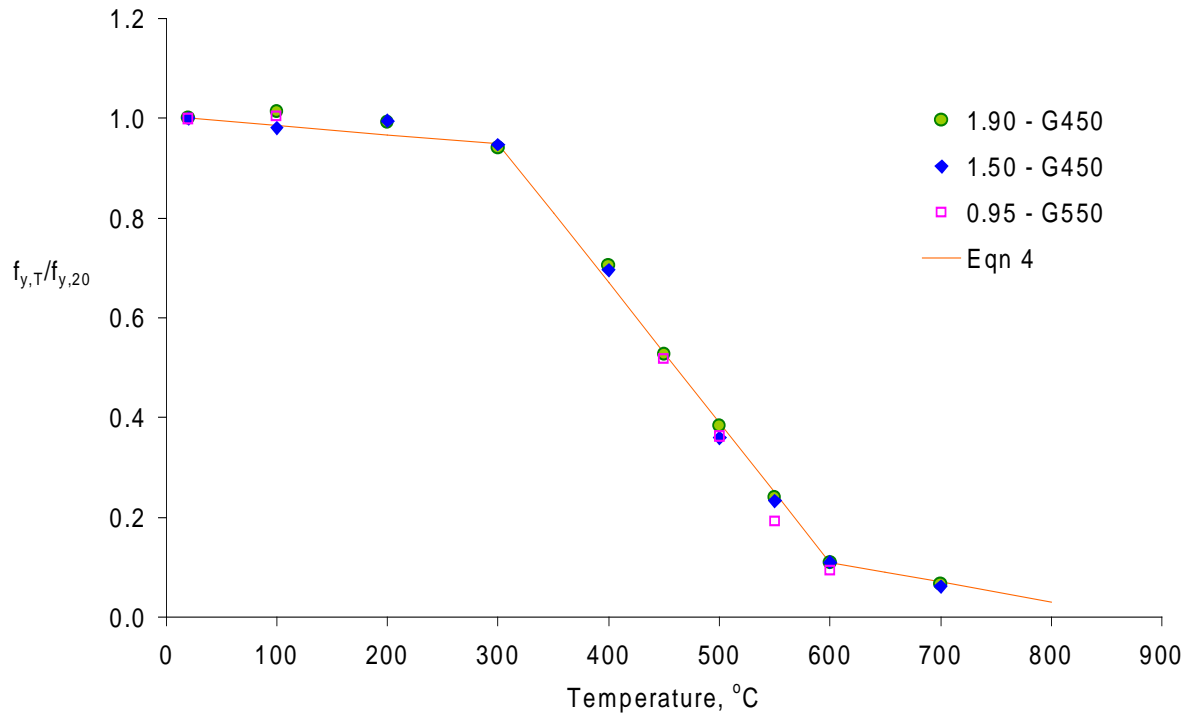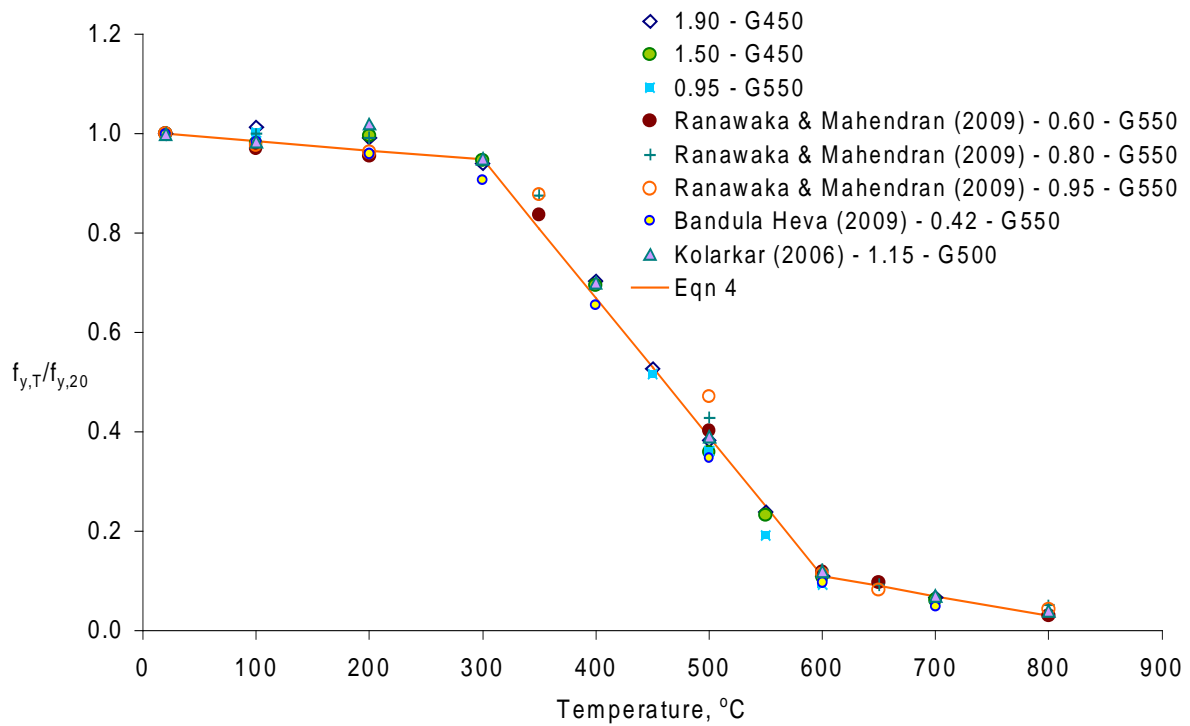**Figure 18: Comparison of Predicted Yield Strength Reduction Factors from Equation 4 with Test Results**

(a) This research

(b) QUT research

Figure 19: Comparison of Predicted Elastic Modulus Reduction Factors with Test Results

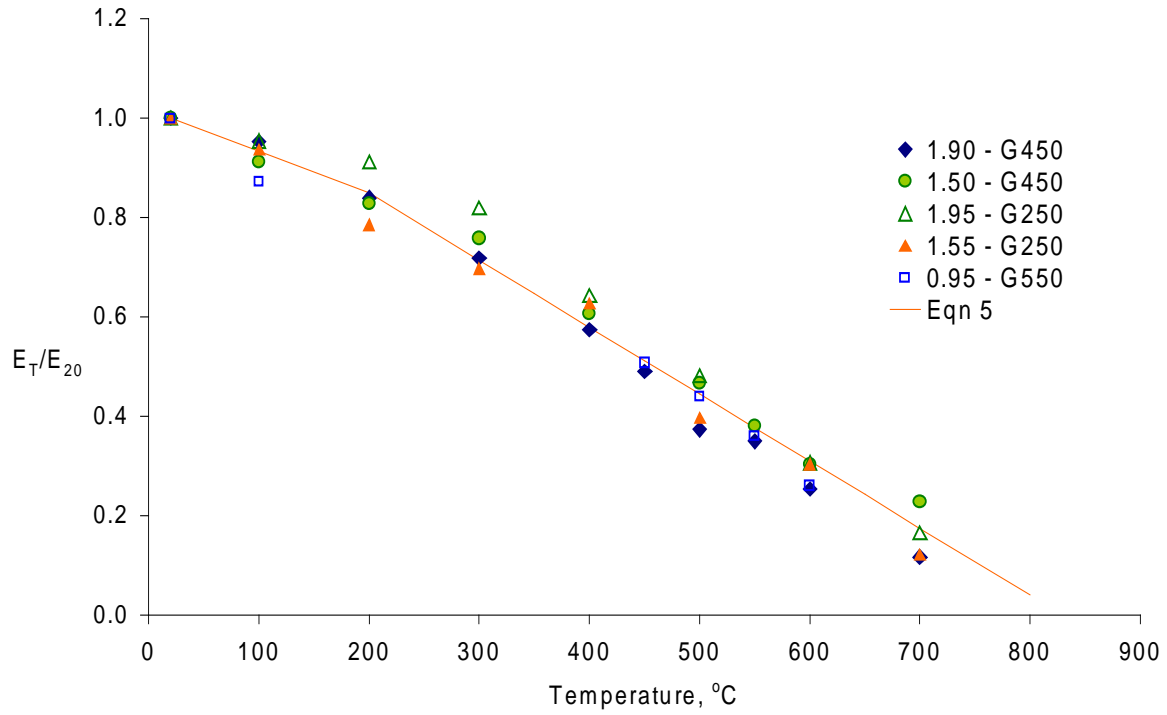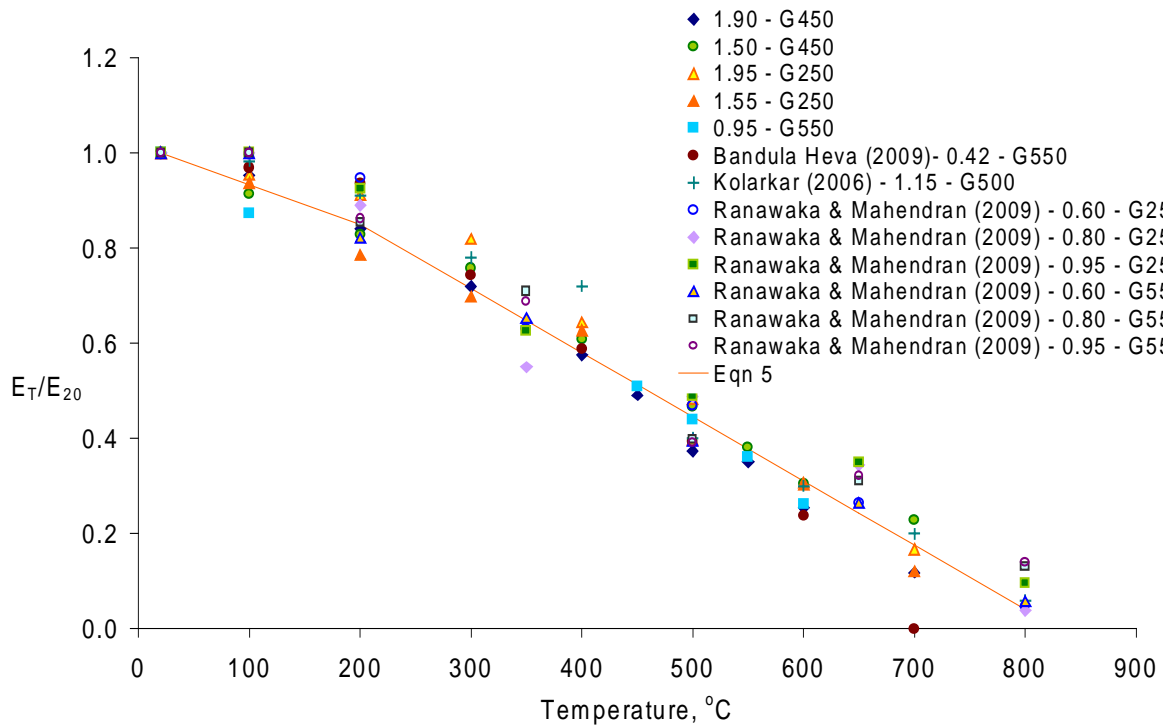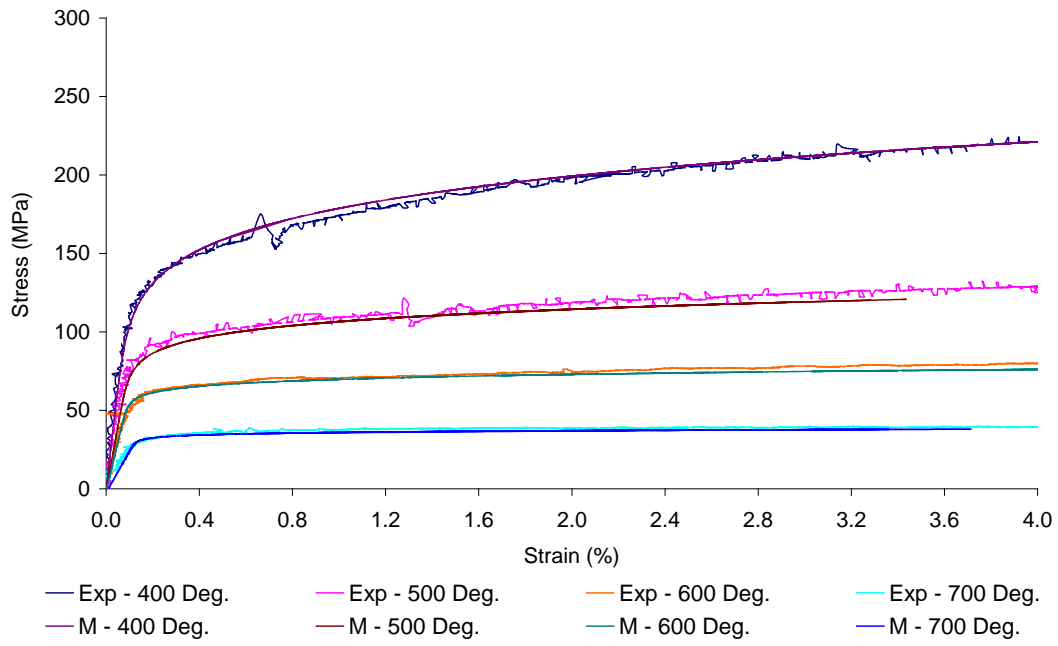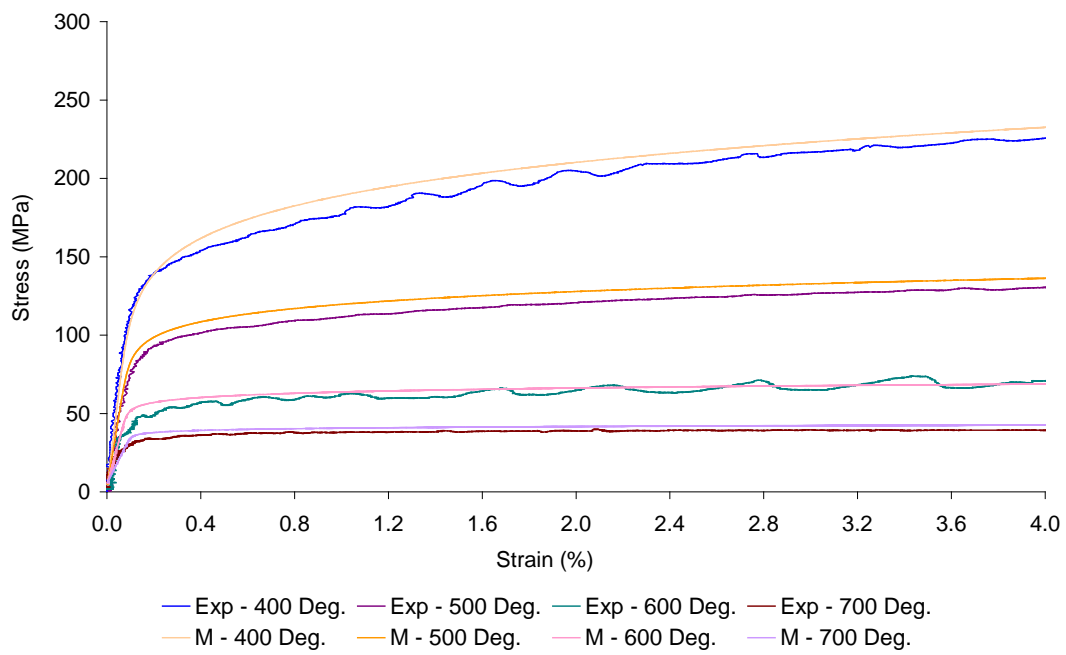(a) 1.55 mm G250 steels

(b) 1.95 mm G250 steels

Note: M – with Modification

Figure 20: Stress-strain Curves based on Equations 6 and 7 with Modified β Value

Table 1: Mechanical Properties at Ambient Temperature

Thickness (mm)	Grade	Elastic modulus (MPa)		Yield strength (MPa)		Ult. strength
		SG	LSE	SG	LSE	LSE
1.55	250	204385	202700	293.50	292.00	361.0
1.50	450	207490	209240	537.11	536.25	561.8
1.95	250	188220	189090	270.51	269.73	356.1
1.90	450	206328	201395	514.50	515.25	542.5
0.95	550	210960	205480	616.00	612.70	634.0
0.42	550	210568	207500	673.82	664.80	700.0
1.15	500	213520	-	569.00	-	589.0
0.60	250	211000	-	314.50	-	370.0
0.80	250	200000	-	297.00	-	365.0
0.95	250	200000	-	320.00	-	361.0
0.60	550	214000	-	675.00	-	700.0
0.80	550	200000	-	610.00	-	635.0
0.95	550	205000	-	615.00	-	625.0

Note: SG: Strain Gauge, LSE: Laser Speckle Extensometer

Table 2: Yield Strength Reduction Factors ($\sigma_{y,T}/\sigma_{y,20}$) at Various Strain Levels

Temp. °C	1.55 mm Grade 250				1.5 mm Grade 450			
	0.2 %	0.5 %	1.5 %	2.0 %	0.2 %	0.5 %	1.5 %	2.0 %
20	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
100	0.951	0.945	0.943	0.947	0.980	0.982	0.991	0.993
200	0.935	0.901	0.938	0.962	0.995	0.975	1.031	1.047
300	0.640	0.678	0.862	0.938	0.947	0.941	1.016	1.018
400	0.492	0.529	0.639	0.675	0.695	0.700	0.748	0.739
500	0.323	0.343	0.385	0.402	0.360	0.382	0.436	0.437
550	-	-	-	-	0.233	0.251	0.294	0.299
600	0.226	0.234	0.253	0.259	0.110	0.120	0.146	0.150
700	0.127	0.129	0.138	0.140	0.061	0.065	0.073	0.074
Temp. °C	1.95 mm Grade 250				1.90 mm Grade 450			
	0.2 %	0.5 %	1.5 %	2.0 %	0.2 %	0.5 %	1.5 %	2.0 %
20	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
100	0.988	0.996	0.997	0.997	1.013	1.032	1.032	1.042
200	0.950	0.955	0.966	1.074	0.991	1.002	1.020	1.028
300	0.726	0.771	0.958	1.035	0.940	0.944	1.013	1.010
400	0.546	0.579	0.687	0.733	0.704	0.711	0.754	0.747
450	-	-	-	-	0.527	0.557	0.601	0.596
500	0.354	0.367	0.410	0.422	0.383	0.414	0.448	0.460
550	-	-	-	-	0.240	0.249	0.302	0.306
600	0.200	0.209	0.226	0.232	0.110	0.119	0.136	0.139
700	0.127	0.129	0.136	0.137	0.066	0.070	0.076	0.077

Table 3: Elastic Modulus Reduction Factors at Elevated Temperatures

Temp. ^{o}C	E_T/E_{20}			
	G250		G450	
	1.55mm	1.95mm	1.50mm	1.90mm
20	1.000	1.000	1.000	1.000
100	0.937	0.954	0.913	0.953
200	0.786	0.912	0.829	0.840
300	0.697	0.820	0.758	0.719
400	0.627	0.644	0.607	0.574
450	-	-	-	0.491
500	0.397	0.482	0.467	0.374
550	-	-	0.380	0.350
600	0.304	0.307	0.304	0.255
700	0.122	0.167	0.229	0.118

Table 4: Ultimate Strength Reduction Factors at Elevated Temperatures

Temp. ºC	$(\sigma_{u,T}/(\sigma_{u,20})$			
	G250		G450	
	1.55mm	1.95mm	1.50mm	1.90mm
20	1.000	1.000	1.000	1.000
100	1.051	1.036	1.000	1.030
200	1.224	1.222	1.063	1.036
300	1.075	1.081	0.997	0.989
400	0.693	0.674	0.717	0.724
450	-	-	-	0.578
500	0.399	0.386	0.426	0.435
550	-	-	0.360	0.304
600	0.237	0.200	0.159	0.164
700	0.116	0.106	0.074	0.077