Effect of temperature and galvanization on cold-formed angles

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ABSTRACT

An experimental program was conducted at the University of Manitoba in order to investigate the effect of subfreezing temperatures and galvanization on the behaviour of cold-formed steel angles. The study involved the testing of 20 cold-formed angles, 55 mm x 55 mm x 4 mm, with a slenderness ratio of approximately 70. Equal numbers of galvanized and ungalvanized angles were tested at various temperatures ranging from -45°C to 25°C. The mechanical properties were obtained through 48 standard tension coupon tests conducted at the same temperature range.

The results showed that the capacity of the angles measured at temperatures below -40°C was approximately 8% higher than the capacity at room temperature. Similar behaviour was also observed during testing of the standard tension coupons where the yield and tensile strengths of the steel used were approximately 10% higher at temperatures below -40°C than at room temperature. On the average, the ultimate capacity of galvanized angles was approximately 9% higher than that of ungalvanized angles. Although the yield strength of the corner coupons was between 13% and 27% higher than that of flat coupons tested at room temperature, the behaviour of the full-size angles was influenced mainly by the properties of the flat regions. A comparison of the measured and predicted capacities using the current Canadian and American Specifications indicated that the Canadian Specification overestimated the ultimate capacity of the angles by as much as 28%, while the American Specification underestimated the capacity by as much as 54%.

Key Words: angles, cold-formed, galvanized, temperature, compression, ultimate
INTRODUCTION

While most experimental work is conducted in research laboratories under controlled conditions, real structures are subjected to a wide range of loading and weather conditions which are often not simulated in a research setting. Hydro-electric towers are one example of structures which must not only be designed to withstand a wide range of loading conditions, but must also be lightweight and maintenance-free. The high strength-to-weight ratio, the simplicity of fabrication, and the ease of erection has made cold-formed steel an attractive material for the construction of such structures. To provide protection from corrosion and to reduce the maintenance costs, either galvanized cold-formed steel members are used, or steel with improved atmospheric corrosion resistance (weathering steel) is chosen. While considerable research has been conducted in the area of steel angles, there is a lack of experimental evidence on the effects of galvanization and temperature, especially subfreezing temperatures, on the behaviour of cold-formed steel angles.

An experimental program sponsored by Manitoba Hydro was conducted at The University of Manitoba in order to investigate the effect of subfreezing temperatures and galvanization on the behaviour of cold-formed steel angles. The study involved the testing of 20 cold-formed angles, 55 mm x 55 mm x 4 mm. All angles were 800 mm long with a slenderness ratio of approximately 70. An equal number of galvanized and ungalvanized angles was tested at various temperatures ranging from -45°C to 25°C. The mechanical properties were obtained through 48 standard tension coupon tests conducted at the same temperature range.

In this paper, results obtained from the current Canadian and American Specifications for the design of cold-formed steel angles are compared to the measured values and recommendations for the design of cold-formed steel angles are presented.

EXPERIMENTAL PROGRAM

In order to evaluate the behaviour of the cold-formed steel angles at subfreezing temperatures, a refrigeration unit was designed and built at the structural laboratory of The University of Manitoba. This unit, shown in Fig. 1, measured 810 mm x 950 mm x 2440 mm, and contained two access holes, 200 mm in diameter, at the top and bottom to accommodate the
hydraulic actuator. The unit was equipped with a Copeland 1.12 kW compressor unit, a serpentine coil evaporator, a hot gas by-pass control, and twin thermostats with a two-pole switch. The unit was designed specifically for this project to maintain a constant temperature during testing. A 4-pane window located in the front door of the refrigeration unit allowed visual inspection of the angle specimens during testing.

Twenty cold-formed angles, ten galvanized and ten ungalvanized angles, were obtained from the open market and tested to failure at various temperature levels ranging from -45°C to 25°C. The measured temperatures and ultimate loads for all the angles tested are given in Table 1. The average cross-sectional dimensions of the tested specimens are shown in Fig. 2(a).

Two types of end connections were investigated. In the first type, the angles were tested as simply supported at both ends and the load was applied via plates connected to one leg of the angles at the ends with single 16 mm A325 bolts located 40 mm from the end of the angles. In this connection, shown in Fig. 3(a), the use of two knife edges perpendicular to each other allowed rotational movement of the specimens but restrained their translational movement at the supports.

The second type of connection, shown in Fig. 3(b), was similar to the first type except that the two knife edges were not used. This type of connection, which is representative of typical tower construction, allowed rotational movement of the specimens only in one direction, while the translational displacement at the ends was restrained.

The loading was applied using a ±1000 kN MTS closed loop system. The instrumentation consisted of two sets of four Linear Variable Differential Transducers (LVDT's) located at midheight and at 3/4-height of the angle specimens to monitor the lateral and rotational displacements, as shown in Fig. 1. In addition, the relative vertical displacement between the ends of the specimens was recorded by measuring the stroke of the hydraulic actuator. The temperature in the refrigeration unit was monitored using a thermocouple. A Hewlett-Packard Data Acquisition System was used to measure and store the data during testing.

To determine the mechanical properties of the specimens, a total of 48 standard tension test coupons were used. The coupons were taken from flat and corner sections of the specimens, as
shown in Fig. 2(b). Standard tests were performed according to ASTM-E8M to obtain the yield strength. The modulus of elasticity was computed according to ASTM-A370-77. In order to determine the physical properties of the specimens tested at various temperature levels, a smaller refrigeration unit was designed and mounted to a 267 kN capacity testing machine, as shown in Fig. 4. The temperature was monitored with the aid of a thermocouple mounted directly on the tension test coupon.

TEST RESULTS AND DISCUSSION

(a) Standard Tension Coupon Tests

Coupons were cut from flat and corner areas of both galvanized and ungalvanized specimens, as shown in Fig. 2(b). The specimens were tested at various temperature levels using the test set-up described earlier. The mechanical properties obtained from these tests are listed in Tables 2 and 3. The following discussion of the results will focus on the effect of galvanizing, cold-forming, and temperature on the mechanical properties of the material.

Effect of Galvanizing

All angles were galvanized by the supplier using the hot-dip galvanizing process after they were roll-formed. The measured yield strength of the galvanized and ungalvanized flat coupons is shown in Fig. 5 as a function of temperature. The average yield strength of galvanized flat coupons was approximately 9% higher than that of ungalvanized coupons at room temperature and 5% higher at subfreezing temperatures. The measured yield strength of the galvanized and ungalvanized corner coupons is shown in Fig. 6. These results indicate that there was no difference between the yield strengths of galvanized and ungalvanized corner coupons at subfreezing temperatures and there was only a 2% difference at room temperature. The measured ultimate strength of the flat and corner coupons is shown in Figs. 7 and 8, respectively. The test results indicate that galvanizing had virtually no effect on the ultimate strength of either flat or corner tension test coupons.
Effect of Cold-Forming

In order to investigate the effect of cold-forming, standard coupons taken from the corner and flat regions of the angles were tested in tension.

The measured yield strength of ungalvanized flat and corner coupons is shown in Fig. 9. As indicated in this figure, the average yield strength of the ungalvanized corners was approximately 27% higher than that of ungalvanized flats at room temperature and 20% higher at temperatures below -40°C. The same trend was observed for the galvanized coupons. As shown in Fig. 10, the average yield strength of the galvanized corners was approximately 13% higher than that of galvanized flats at room temperature and 14% higher at temperatures below -40°C. The supplier of the specimens used in this experimental program did not provide a mill report. However, the yield strength of the virgin steel was specified as 300 MPa. The measured average yield strength of the ungalvanized flats at room temperature was 414 MPa which was 38% higher than the yield strength specified by the supplier. Similarly, the average yield strength of the ungalvanized corners at room temperature was 527 MPa, which was 76% higher than the specified yield strength. These results confirmed the findings by Karren and Winter (1967) who reported that the yield strength of flats and corner coupons they tested were, respectively, 53% and 102% higher than that of the virgin metal.

The measured ultimate strength for both galvanized and ungalvanized coupons is shown in Figs. 11 and 12, respectively. As indicated in these figures, the average ultimate strength of both galvanized and ungalvanized corner coupons was approximately 7% higher than flat coupons at all temperature levels.

Effect of Temperature

The prime objective of the research project reported herein was to determine whether subfreezing temperatures had any effect on the behaviour of cold-formed steel angles. As shown in Fig. 5, the yield strength of both galvanized and ungalvanized flat coupons increased by approximately 6% and 9%, respectively, at subfreezing temperatures. The increase in yield strength of the corner coupons was somewhat smaller, 5% for galvanized coupons and 3% for
ungalvanized coupons, as shown in Fig. 6. The ultimate strength of both corner and flat coupons was also higher at subfreezing temperatures than at room temperature. The average ultimate strength of the tension test coupons was approximately 10% higher at subfreezing temperatures than at room temperature, as shown in Figs. 11 and 12.

(b) Full Size Specimens

The measured ultimate loads of all angles tested in this experimental program are given in Table 1. The primary mode of failure observed for the specimens was yielding caused by continuous bending and twisting without any local buckling, as shown in Fig. 13. All specimens began to bend and twist at the onset of first loading.

In order to evaluate the results from the testing of the full size specimens, column curves based on the measured average dimensions of the specimens were developed, as given in Figs. 14(a) and 14(b). These curves were developed on the basis of the Euler formula for lateral buckling in the elastic range and the Column Research Council (CRC) formula for lateral buckling in the inelastic range assuming concentrically applied loading. More specifically, the critical ultimate load, \( P_{cr} \), expressed in terms of the cross sectional area \( A \), is as follows:

\[
[1] \quad P_{cr} = f_{cr} A
\]

where

\[
[2] \quad f_{cr} = (f_{cr})_{elastic} = \frac{x^2E}{(L/r)^2} \quad \text{if} \quad f_{cr} \leq f_p
\]

and

\[
[3] \quad f_{cr} = (f_{cr})_{inelastic} = F_y - \frac{f_r(F_y - f_r)}{f_{cr}}_{elastic} \quad \text{if} \quad f_{cr} > f_p
\]
where \( f_r \) is the maximum compressive residual stress in the section, \( F_y \) is the yield stress of the material, \( L \) is the unbraced length of the member, and \( r \) is the least radius of gyration. Equation 2 represents the elastic behaviour while Eq. 3 represents the inelastic behaviour of the columns. The transition between the two behaviours takes place at a stress which corresponds to the proportional limit of stress, \( f_p \), where \( f_p = F_y - f_r \). Current specifications for the design of compression members assume \( f_r = F_y/2 \). This is also the value used in developing the column curves shown in Figs. 14(a) and 14(b).

The three curves shown in Figs. 14(a) and 14(b) for the inelastic range of member behaviour correspond to three yield strengths. Curve A was developed using \( F_y = 300 \) MPa, the yield stress specified by the supplier. Curve B was developed using the average yield stress obtained from the flat coupons tested at room temperature. Curve C was based on a composite yield strength computed according to the AISI Specification (AISI 1986) which takes into account the yield strengths of both flat and corner coupons tested at room temperature.

The experimental results for both galvanized and ungalvanized angles are also shown in these figures. It is evident from Figs. 14(a) and 14(b) that treating the angles as concentrically loaded compression members leads to an overestimation of their ultimate capacity. While the reduced capacity may be attributed mainly to the eccentricity of the applied load, other factors such as galvanization, cold work, and temperature also influenced the ultimate capacity of the angles. These factors are discussed below.

**Effect of Galvanization**

The measured loads for both galvanized and ungalvanized angles are shown in Fig. 15 as a function of temperature. The results indicate that the average ultimate capacity of galvanized angles was approximately 9% higher than that of ungalvanized angles at room temperature and approximately 8% higher at temperatures below \(-45^\circ C\).

**Effect of Cold-Work**

The process of cold-forming results in considerable alteration of the mechanical properties of steel. This was evident in the results from the tension test coupons where the yield strength and
ultimate tensile strength of the corners were higher than those of the flat regions. Thus, the behaviour of a cold-formed member is the result of the composite action of the various elements, corner and flats, that make up the sections (Karren and Winter 1967). Both the Canadian and American Specifications allow the designer to use, in some cases, a higher yield strength for the design of cold-formed sections to account for the high yield strength of the corners (CSA 1984, AISI 1986). In the current experimental program, the yield strengths of galvanized and ungalvanized angles, computed on the basis of the results from both the flat and corner tension test coupons, were 457 MPa and 430 MPa, respectively. These values are only 2% higher than the average yield stress obtained from the flat tension test coupons. Consequently, the behaviour of the full size angles could be considered to be influenced mainly by the mechanical properties of the flat regions.

**Effect of Temperature**

To examine the effect of temperature on the behaviour of the angle specimens, the measured ultimate loads for all tested angles are shown in Fig. 15 as functions of temperature. The behaviour indicates that, on the average, the ultimate capacity of galvanized and ungalvanized angles was approximately 7% and 9% higher, respectively, at temperatures below -40°C than at room temperature. This behaviour was also observed in the tension coupon tests discussed earlier.

**END CONNECTIONS**

As described earlier, two types of end supports were investigated in this experimental program. The first type of support condition was designed to provide rotational movement to the members about the knife edges. However, it was observed that after an initial rotation about one of the knife edges, the member began to rotate about the bolt, resulting in considerable local distortion in the vicinity of the bolt. A typical behaviour of a member with this type of support is shown by Curve A in Fig. 16, where the stroke of the hydraulic actuator is shown as a function of the applied load.

In the second type of end connection, where the knife edges were completely removed, the members were allowed to rotate about the bolts. A typical behaviour of a member with this type of
connection is shown by Curve B in Fig. 16. All specimens whose results are reported here were tested using the second type of connection. This support condition closely simulates the type of connection used in actual prototype structures by Manitoba Hydro. Angles tested with this type of connection exhibited higher ultimate capacity than those tested with the first type of end connection, as shown in Fig. 16.

EVALUATION OF CANADIAN AND AMERICAN SPECIFICATIONS

(a) The Canadian Specification

The Canadian Specification CSA-S136-M84 for Cold-formed Steel Structural Members (CSA 1984) treats single angles loaded through one leg as compression members subject to lateral-torsional buckling. An equivalent slenderness ratio which combines the effects of bending about the weak axis and twisting is used in the calculations. According to the Canadian Specification, the factored compressive resistance of angles, $C_r$, not subject to local buckling, is computed in terms of the cross sectional area, $A$, and the resistance factor, $\phi_a$, as follows:

\[ C_r = \phi_a A F_a \leq C_{r, \text{max}} \]

where $F_a$ is the critical stress, which is computed as follows:

\[ F_a = F_y - \frac{F_y^2}{4F_p} \quad \text{if} \quad F_p > \frac{F_y}{2} \]

\[ F_a = F_p \quad \text{if} \quad F_p \leq \frac{F_y}{2} \]

where

\[ F_p = 0.833 \frac{\pi^2 E}{\left[ \left( \frac{KL}{F_y} \right)^2 + \left( \frac{5b}{t} \right)^2 \right]} \]
The term $r_v$ used in Eq. 7 is the least radius of gyration, $b$ is the outstanding width of the larger leg, $t$ is the leg thickness and $K$ is the effective length factor. For translation-fixed connections using a single bolt, an effective length factor, $K$, of 0.8 is used while for translation-fixed connections using welds or two or more bolts an effective length factor of 0.7 is used. The compressive resistance factor, $\phi_a$, used in Eq. 4 is equal to 0.75 while the maximum compressive resistance, $C_{r,max}$, depends on the type of end connection used. For members loaded through a single bolt, $C_{r,max} = 0.5 \Delta F_y$, while for members loaded through welds or multiple bolts, $C_{r,max} = 0.67 \Delta F_y$. The nominal resistance can be computed from Eq. 4 using $\phi_a = 1.0$.

The predicted factored and nominal resistances of both galvanized and ungalvanized angles as a function of length are shown in Figs. 17 and 18. The factored resistance was computed using Eq. 4 with a resistance factor, $\phi_a$, equal to 0.75. The computed nominal resistance capacity was based on a resistance factor of unity. The average cross-sectional dimensions of the angles shown in Fig. 2(a) were used to compute these compressive resistances. The curves shown in Figs. 17(a) and 18(a) were developed on the basis of a yield strength of 300 MPa specified by the supplier, whereas the curves shown in Figs. 17(b) and 18(b) were developed using a composite average yield strength obtained through standard flat and corner coupons. The measured ultimate loads for the specimens tested are also shown in these figures.

The results indicate that the Canadian Specification overestimated the ultimate capacity of the galvanized angles by an amount ranging from 0% to 14% when the yield strength specified by the supplier was used, and by an amount ranging from 13% to 28% when the yield strength obtained through standard coupon tests was used. In the case of the ungalvanized angles, the Canadian Specification overestimated their capacity by the same range as that of galvanized angles, i.e., 0% to 14% when the specified yield strength was used and by an amount ranging from 16% to 31% when the yield strength obtained from the coupons was used.
(b) The American Specification

The 1980 edition of the American Specification (AISI 1980) required that the design of singly-symmetric shapes such as angles, subject to both axial compression and bending applied out of the plane of symmetry be based on testing. In the last edition of the same Specification (AISI 1986), this requirement for testing was removed and the design of single angles was incorporated under the same provisions as those governing the design of beam-column members. Interaction formulae for strength and stability based on the allowable stress design approach are given in this Specification to check the adequacy of singly symmetric angles. To compute the allowable axial stress, an effective length factor, $K$, of 1.0 along with a factor of safety which varies between 1.67 and 1.92, depending on the slenderness ratio of the angles and the yield strength of the material, are recommended. The allowable bending stress is based on a safety factor of 1.67. To account for the effect of out-of-straightness, the American Specification requires an additional moment be applied about the axis perpendicular to the axis of symmetry.

The ratio between the measured ultimate loads of the tested angles and the ultimate capacity computed according to the American Specification (AISI 1986) with a factor of safety of 1.0 is shown in Figs. 19(a) and 19(b). When the yield strength obtained from the tension test coupons was used, the ratio varied from 1.41 to 1.61 for the galvanized angles and from 1.43 to 1.62 for ungalvanized angles, as shown in Fig. 19(a). However, when the yield strength specified by the supplier was used, the ratio ranged from 1.92 to 2.15 for the galvanized angles, and from 1.90 to 2.15 for ungalvanized angles, as shown in Fig. 19(b).

These results indicate that the American Specification is quite conservative in predicting the ultimate capacity of cold formed steel angles. For both galvanized and ungalvanized angles the ultimate capacity computed according to the Specification was underestimated by an amount ranging from 48% to 54% when the yield strength obtained through standard coupons was used, and from 29% to 38% when the yield strength specified by the supplier was used.
SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

An experimental program was conducted at The University of Manitoba in order to investigate the effect of subfreezing temperatures and galvanization on the behaviour of cold-formed steel angles. The study involved the testing of 20 cold-formed angles, 55 mm x 55 mm x 4 mm, 800 mm long. An equal number of galvanized and ungalvanized angles were tested at various temperatures ranging from -45°C to 25°C. The mechanical properties of the angles tested were obtained through 48 standard tension coupon tests conducted at the same temperature range as for the full size angles. In addition, the current Canadian and American design guidelines for cold-formed steel angles were evaluated through comparison with the measured values.

Based on the results from the experimental program, the main findings can be summarized as follows:

(1) Standard Tension Coupon Tests

Effect of Galvanization
(a) The average yield strength of galvanized flat coupons was approximately 9% higher than that of ungalvanized flat coupons tested at room temperature and 5% higher at subfreezing temperatures.
(b) There was only a 2% difference between the yield strength of galvanized corner coupons and the yield strength of ungalvanized corner coupons at room temperature. There was very little difference at subfreezing temperatures.
(c) There was no difference between the average ultimate strength of galvanized flat and corner coupons and ungalvanized coupons at all temperature levels.

Effect of Cold-Forming
(a) For ungalvanized angles, the average yield strength of corner coupons was approximately 27% higher than that of flat coupons when tested at room temperature and 20% higher at temperatures below -40°C.
(b) For galvanized angles, the average yield strength of corner coupons was approximately 13% higher than that of flat galvanized coupons at room temperature and approximately 14% higher at temperatures below -40°C.

(c) The average yield strength of the ungalvanized flat coupons tested at room temperature was approximately 38% higher than the yield strength of the virgin metal as specified by the supplier.

(d) The average yield strength of the ungalvanized corner coupons was approximately 76% higher than the yield strength specified by the supplier for the virgin metal.

(e) The average ultimate strengths of both galvanized and ungalvanized corner coupons were approximately 7% higher than those of flat coupons at all temperature levels.

Effect of Temperature

(a) The average yield strength of galvanized flat coupons was approximately 6% higher at temperatures below -40°C than at room temperature.

(b) The average yield strength of ungalvanized flat coupons was approximately 9% higher at temperatures below -40°C than at room temperature.

(c) The yield strengths of galvanized and ungalvanized corner coupons were approximately 5% and 3% higher, respectively, at temperatures below -40°C than at room temperature.

(d) The average ultimate strengths of corner and flat coupons, both galvanized and ungalvanized, were approximately 10% higher at subfreezing temperatures than at room temperature.

(2) Full Size Specimens

Effect of Galvanization

(a) On the average, the ultimate capacity of galvanized angles was approximately 8% to 9% higher than that of ungalvanized angles.

Effect of Temperature

(a) On the average, the ultimate capacity of both galvanized and ungalvanized angles was approximately 7% to 9% higher at temperatures below -40°C than at room temperature.
General Behaviour

(a) The method used to connect the angles at the supports had a marked effect on their behaviour and their load bearing capacity. The single angles attached through one leg behaved more like beam-columns rather than as concentrically loaded columns.

(b) The average yield strengths of galvanized and ungalvanized angles, computed on the basis of the yield strengths obtained from the testing of flat and corner coupons were only 2% higher than the average yield strengths of the flat coupons. Thus, the behaviour of the full size angles was influenced mainly by the mechanical properties of the flat regions.

(c) The Canadian Specification overestimated the ultimate load for the galvanized angles by an amount ranging from 13% to 28% when the yield strength obtained from standard coupon tests was used, and by an amount ranging from 0% to 14% higher when the yield strength specified by the supplier was used. In the case of ungalvanized angles, the Canadian Specification overestimated their ultimate load by an amount ranging from 16% to 31% when the yield strength obtained from standard coupons was used, and by an amount ranging from 0% to 14% higher when the specified yield strength was used.

(c) The American Specification underestimated the ultimate capacity of both galvanized and ungalvanized angles by an amount ranging from 48% to 54% when the yield strength obtained through standard coupons was used and by an amount ranging from 29% to 38% when the specified yield strength was used.

Based on these findings, it is clear that the current provisions in the Canadian Specification (CSA 1984) for the design of single angles should be revised to reflect member behaviour more realistically. It is recommended that single angles be designed according to the guidelines related to beam-columns. These guidelines are listed in the current Canadian Specification for members other than angles. The experimental program discussed in this paper dealt with equal leg angles that are not subject to local buckling. Further research is required to investigate the effect of local buckling on the ultimate capacity of angles. Additional research is also required to examine the effect of
galvanization, cold work, and temperature on the behaviour of thicker angles under both static and cyclic loading.

ACKNOWLEDGEMENT

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LIST OF SYMBOLS

The following symbols are used in this paper:

A  cross sectional area
b  outstanding width of the larger leg
Cr  factored compressive resistance
(Cr)max  maximum compressive resistance
E  modulus of elasticity
Fa  defined in Eqs. 5 and 6
fcr  critical buckling stress
(fcr)elastic  elastic critical buckling stress
(fcr)inelastic  inelastic critical buckling stress
fp  proportional limit of stress
Fp  elastic lateral-torsional buckling stress
fr  residual stress
Fy  yield stress
K  effective length factor
L  unbraced length
Pcr  buckling load
r, rv  least radius of gyration
t  thickness of section
φa  resistance factor
Table 1. Summary of Results from Angle Tests

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Table 2. Summary of Results from Flat Tension Coupon Tests

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Table 3. Summary of Results from Corner Tension Coupon Tests

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(Numbers in brackets refer to galvanized sections)

(a) Average cross-sectional dimensions

(b) Location of standard coupons
The graph shows the relationship between ultimate strength (in MPa) and temperature (in degrees Celsius) for galvanized and ungalvanized materials. The graph indicates a decrease in ultimate strength with increasing temperature. The data points are plotted as squares for galvanized (GALV) and triangles for ungalvanized (UNGAL) materials.
YIELD STRESS (MPa)

TEMPERATURE (Degrees C)

-60 -40 -20 0 20 40

FLAT
CORNER

[Graph showing the relationship between yield stress and temperature for flat and corner regions]
A : $F_y = 300 \text{ MPa}$
B : $F_y = 450 \text{ MPa}$
C : $F_y = 457 \text{ MPa}$

\[ \Delta \text{ Test Results} \]

(a) Galvanized angles

A : $F_y = 300 \text{ MPa}$
B : $F_y = 414 \text{ MPa}$
C : $F_y = 430 \text{ MPa}$

\[ \Delta \text{ Test Results} \]

(b) Ungalvanized angles
A: 1 Bolt. With knife edges
B: 1 Bolt. Without knife edges
(a) Using specified yield strength

(b) Using yield strength obtained through standard coupon tests
a) Using specified yield strength

- Test results
- $F_y = 300\, \text{MPa}$

Nominal Compressive Resistance

Factored Compressive Resistance

(b) Using yield strength obtained through standard coupon tests

- Test results
- $F_y = 430\, \text{MPa}$

Nominal Compressive Resistance

Factored Compressive Resistance
(a) Using yield strength obtained through standard coupon tests

(b) Using specified yield strength