ABSTRACT

An experimental program was conducted at the University of Manitoba, Canada, in order to investigate the effect of subfreezing temperatures on the behaviour of galvanized and ungalvanized cold-formed steel angles. The specific objectives were to study the influence of temperature, cold work, and galvanization on the behaviour of cold-formed steel angles. The study involved testing of 20 cold-formed angles, 55 mm x 55 mm x 4 mm, with a slenderness ratio of approximately 70. Equal number 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 tensile coupon tests conducted at the same temperatures range.

The results indicated that the yield and tensile strengths of the steel used was approximately 10% higher at temperatures below -40°C than at room temperature. A similar behaviour was also observed in the testing of the full size angles. The results showed that the measured capacity of the galvanized angles was approximately 9% higher than that of ungalvanized angles. For the ungalvanized and galvanized angles, the yield strengths of the corner coupons were 27% and 13%, respectively, higher than those of flat coupons tested at room temperature. A comparison between the measured and predicted capacities using the current North 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%.

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INTRODUCTION

Cold-formed steel members provide substantial savings due to their high strength-to-weight ratio. As a result, they have become very popular in the construction of industrial, commercial and agricultural buildings. Recently, cold-formed steel angles have become an attractive alternative to the traditional hot-rolled angles in the construction of transmission and hydro-electric towers. The major advantage in using cold-formed steel is the savings associated with the cost of transportation and erection of such structures in remote areas of the country. To provide protection from corrosion and to reduce the maintenance costs, cold-formed steel members are normally galvanized or steel with improved atmospheric corrosion resistance (weathering steel) is used.

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, for example, are subject to large temperature fluctuations which could affect the performance and ultimate capacity of the structural elements. Furthermore, there is a lack of experimental evidence on the behaviour of galvanized cold-formed angles in subfreezing temperatures.

In this paper, the results from an ongoing experimental program conducted at the University of Manitoba, Canada, are presented and analyzed. The paper also includes a review of the current Canadian and American Specification requirements for the design of cold-formed steel angles and a comparison between the measured and the computed values. A number of recommendations for future work and for improving the current design Specifications are also made.

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 200 mm access holes 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 bypass control, and twin thermostats with a two-pole switch. It was
designed specifically for this project to maintain 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 steel angles, ten galvanized and ten ungalvanized angles, were tested
to failure at various temperature levels ranging from -45°C to 25°C, as shown in Table 1. The
average dimensional properties of the specimens are shown in Fig. 2(a). The specimens were
obtained from the open market and were galvanized by the supplier.

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. The
simple type connection, shown in Fig. 3(a), was achieved through the use of two knife edges,
perpendicular to each other, which allowed rotational movement of the specimens but restrained
their translational movement at the supports.

The second type 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 Transformers (LVDT's) located at
midheight and at 3/4-height to monitor the lateral and rotational displacements of the angle
specimens, 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 with a thermocouple and a Hewlett-Packard Data Acquisition
System was used to 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 and the modulus of elasticity was computed according to ASTM A370-77. In order to evaluate the physical properties of the specimens tested at various temperature levels, a smaller refrigeration unit, shown in Fig. 4, was designed and mounted to a 267 kN capacity testing machine. Using a thermocouple mounted directly on the tension test coupon, the temperature was monitored and recorded along with the measured applied load and the elongation from an extensometer mounted on the specimen.

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 through these tests are listed in Tables 2(a) and 2(b). 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 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 galvanized and ungalvanized coupons is shown in Figs 7 and 8. The test results indicate that galvanizing had, practically, no effect on the ultimate strength of either flat or corner tension test coupons.
Effect of Cold-Forming

The various methods of cold-forming, such as roll and brake forming, bring about changes in the mechanical properties of steel. Therefore, its prior metallurgical history and the magnitude of plastic strains caused by the cold work must be studied in order to understand the material properties of cold-formed steel material.

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 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, as shown in Fig. 10. The supplier of the specimens used in this experimental program did not provide a mill report but specified the yield strength of the virgin steel as 300 MPa. The measured average yield strength of the ungalvanized flats at room temperature was 414 MPa which is 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 confirm the findings reported by Karren and Winter (Karren and Winter 1967) who reported that the yield strength of flats and corner coupons they tested were 53% and 102% respectively, 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.

Based on an extensive experimental program, Karren (Karren 1967) approximated the tensile yield strength of cold-formed sections as follows:
\[ F_{ya} = CF_{yc} + (1-C) F_{yf} \]  \[1\]

where \( F_{yc} \) is the average tensile yield strength of corners, \( F_{yf} \) is the average tensile yield strength of flats, and \( C \) is the ratio of corner area to total cross sectional area.

Equation 1 has been adopted by the American Specification (AISI 1986) for use with sections which are not subject to local buckling.

Lind and Schroff (Lind and Schroff 1975) studied Karren's experimental data (Karren 1967) by using a linear strain-hardening model. As a result, the following equation used to compute the average tensile yield strength \( F_y \) of the full section of tension or compression members was suggested:

\[ F_y = F_y + \frac{5D}{W} (F_u - F_y) \]  \[2\]

where \( F_u \) and \( F_y \) are the ultimate and yield strengths of the virgin material, respectively, \( D \) is the number of 90° corners and \( W \) is the ratio of the centerline length of the entire section in compression to the thickness \( t \).

Equation 2 has been adopted by the Canadian Specification (CSA 1984) for use in sections that are not subject to local buckling.

**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 coupon increased by approximately 6% and 9% respectively at subfreezing temperatures. The increase in yield strength of the corner coupons was only 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. As shown in Figs. 11 and
12, the average ultimate strength of the tension test coupons was approximately 10% higher at subfreezing temperatures than at room temperature.

(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 of all specimens was yielding caused by continuous bending and twisting, as shown in Fig. 13, without any local buckling. 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 nominal dimensions of the specimens were developed, as shown 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, it was assumed that,

\[ P_{cr} = f_{cr} A \]  \hspace{1cm} [3]

where \[ f_{cr} = (f_{cr})_{\text{elastic}} = \frac{\pi^2 E}{(L/r)^2} \] if \[ f_{cr} \leq F_Y \] \hspace{1cm} [4]

and \[ f_{cr} = (f_{cr})_{\text{inelastic}} = F_Y - \frac{f_r (F_Y - f_r)}{(f_{cr})_{\text{elastic}}} \] if \[ f_{cr} > F_Y \] \hspace{1cm} [5]

Where \( f_r \) is the maximum compressive residual stress in the section, \( F_Y \) is the yield stress of the material, \( A \) is the cross sectional area of the member, \( L \) is the unbraced length of the member, and \( r \) is the least radius of gyration. Equation 5 represents the inelastic behaviour of the columns while Eq. 4 represents the elastic behaviour. 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). Three curves are shown for
the inelastic range of member behaviour: 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 stress
of both flat and corner coupons tested at room temperature, computed according to the AISI
Specification (AISI 1986). The experimental results for both galvanized and ungalvanized angles
are also shown in these figures. It is evident from these figures 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 effect of galvanization can be evaluated using Fig. 15. The results suggest that, in
general, galvanized angles exhibited higher capacity than ungalvanized angles. As shown in the
same figure, the average ultimate capacity of galvanized angles was approximately 9% higher than
ungalvanized angles at room temperature and 8% higher at temperatures below -45°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). Current design
specifications allow the designer to use, in some cases, a higher yield strength for the design of
cold-formed sections which accounts for the high yield strength of the corners. 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, according to Eq. 1 were 457 MPa and 430 MPa, respectively. These are only 2% higher than the average yield stress obtained from the flat tension test coupons. Consequently, the behaviour of the full size angles was 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.

END CONNECTIONS

Two types of end supports were investigated in this experimental program, as described earlier. 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 as Curve A in Fig. 16, where the stroke of the hydraulic actuator is shown as a function of the applied load.

The second type of end connection, where the knife edges were completely removed, the members were allowed to rotate about the bolts, as shown in Fig. 3(b). A typical behaviour of a member with this type of connection is shown as Curve B in Fig. 16. All specimens tested in this experimental program, whose results are reported here, were tested using the second type of connection.
EVALUATION OF CANADIAN AND AMERICAN SPECIFICATIONS THROUGH COMPARISON WITH THE EXPERIMENTAL RESULTS

(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. The factored compressive resistance of angles, $C_r$, not subject to local buckling is computed as follows:

$$C_r = \phi_a A F_a \leq C_{r,\text{max}}$$  \[6\]

where

$$F_a = \begin{cases} F_y - \frac{F_y^2}{4F_p} & \text{if } F_p > \frac{F_y}{2} \\ F_p & \text{if } F_p \leq \frac{F_y}{2} \end{cases}$$  \[7\]

and

$$F_p = 0.833 \frac{\pi^2 E}{\left(\frac{r_v K L^2}{r_v^2} + \left(\frac{5b^2}{t}\right)^2\right)}$$  \[9\]

where $r_v$ 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 $K = 0.8$ is used while for translation-fixed connections using welds or two or more bolts, $K = 0.7$ is used.

The compressive resistance factor, $\phi_a$, used in Eq. 6 is equal to 0.75 while the maximum compressive resistance, $C_{r,\text{max}}$, depends on the method of connection at the ends. For members loaded through a single bolt, $C_{r,\text{max}} = 0.5 A F_y$, while for members loaded through welds or multiple bolts, $C_{r,\text{max}} = 0.67 A F_y$.

The ultimate unfactored resistance can be completed from Eq. 6 using $\phi_a = 1.0$. 
The factored and unfactored compressive resistances of both galvanized and ungalvanized angles are shown in Figs. 17 and 18 as functions of length. The factored resistance was computed using Eq. 6 with a resistance factor, $\phi_a$, equal to 0.75. The unfactored resistance capacity was computed without the resistance factor $\phi_a$. 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 the yield strength 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 coupon was used.

(b) The American Specification

The earlier 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 should be based on testing. In the 1986 Edition of the same Specification (AISI 1986) the requirement for testing was removed and the design of single angles was incorporated under the same provisions as those governing the design of all beam-columns. Interaction formulae for strength and stability based on the allowable stress design approach were developed to check the adequacy of singly symmetric angles.
The following interaction formula is used for stability check:

\[
\frac{P}{P_a} + \frac{C_{mx} M_x}{M_{ax} \left( 1 - \frac{\Omega P}{P_{cr,x}} \right)} + \frac{C_{my} M_y}{M_{ay} \left( 1 - \frac{\Omega P}{P_{cr,y}} \right)} \leq 1.0
\]  \hspace{1cm} [10]

where \( P_a \) is the allowable axial load in the absence of any bending moment; \( M_{ax} \) and \( M_{ay} \) are the allowable bending moments about the \( x \) and \( y \) axis, respectively, in the absence of any axial load; \( P_{cr,x} \) and \( P_{cr,y} \) are the elastic buckling loads about the principal \( x \) and \( y \) axis, respectively; \( C_{mx} \) and \( C_{my} \) are coefficients whose values depend on the type of loading and the type of end supports. For individual members subjected to combined axial compressive load and uniform bending moment; these coefficients are equal to unity. \( P \) is the applied axial load and \( M_x \) and \( M_y \) are the applied moments about the \( x \) and \( y \) axis, respectively. These are computed as follows:

**Allowable axial load \( P_a \)**

Equal leg angles loaded concentrically will fail in one of two modes: by lateral buckling about the \( y \) axis or by a combination of lateral buckling about the axis of symmetry, \( x \), and twisting. The allowable load is defined as:

\[
P_a = \frac{P_n}{\Omega_c}
\]  \hspace{1cm} [11]

where \( P_n \) is the ultimate critical load and \( \Omega_c \) is the factor of safety. For angles which are not subject to load buckling,

\[
P_n = A f_a
\]  \hspace{1cm} [12]

where \( f_a \) is the buckling stress. Buckling may take place in the elastic or the inelastic range of member behaviour. Thus, \( f_a \) is defined as:
\[ f_a = F_y \left[ 1 - \frac{F_y}{4f_{cr}} \right] \quad \text{if} \quad f_{cr} \geq \frac{F_y}{2} \]  

or

\[ f_a = f_{cr} \quad \text{if} \quad f_{cr} < \frac{F_y}{2} \]  

where \( F_y \) is the yield stress and \( f_{cr} \) is the smaller of either the elastic lateral buckling stress about the y-axis,

\[ f_y = \frac{\pi^2 E}{(KL/r)_y^2} \]  

or the elastic later-torsional buckling stress,

\[ f_{lx} = \frac{1}{2\alpha} \left[ (f_x + f_t) - \sqrt{(f_x + f_t)^2 - 4\alpha f_x f_t} \right] \]  

where

\[ \alpha = 1 - \left( \frac{r_o}{r_0} \right)^2 \]  

and \( f_t \) and \( f_x \) are the elastic torsional stress and lateral buckling about the x-axis stress, respectively. These are defined as:

\[ f_t = \frac{1}{Ar_o^2} \left[ GJ + \frac{\pi^2 E C_w}{(K_i L o)^2} \right] \]  

\[ f_x = \frac{\pi^2 E}{(KL/r)_x^2} \]  

where

\[ r_0 = \sqrt{r_x^2 + r_y^2 + x_0^2} \]
$K_x, K_y, K_t$ = effective length factors for bending about the $x$ and $y$ axes and for twisting.

$L_x, L_y, L_t$ = unbraced length of angle for bending about the $x$ and $y$ axes for twisting.

$r_x, r_y$ = radii of gyration about the $x$ and $y$ axes, respectively.

$x_0$ = distance between the shear center and the centroid along the $x$-axis.

$J$ = St. Venants torsion constant

$C_w$ = warping constant

$G$ = shear modulus of elasticity

$E$ = elastic modulus.

The factor of safety, $\Omega_c$, used in Eq. 11 to compute the allowable load, is 1.92 except when the mode of failure is by inelastic lateral buckling and the section’s thickness exceeds 2.3 mm and is not subject to local buckling. In this case the safety factor is computed as follows:

$$\Omega = \frac{5}{3} + \frac{3}{8}R - \frac{1}{8}R^3$$ \hspace{1cm} [21]

where

$$R = \sqrt{\frac{F_y}{2f_{cr}}}$$ \hspace{1cm} [22]

**Allowable bending moment $M_{ax}$**

The allowable bending moment about the axis of symmetry $x$ is computed as follows:

$$M_{ax} = \frac{M_{nx}}{\Omega_f}$$ \hspace{1cm} [23]

where $M_{nx}$ is the critical lateral-torsional buckling moment defined as:

$$M_{nx} = M_{ylx} \left( 1 - \frac{M_{ylx}}{4M_{ox}} \right) \hspace{1cm} \text{if} \hspace{0.5cm} M_{ex} > 0.5 M_{ylx}$$ \hspace{1cm} [24]
and \[ M_{nx} = M_{ex} \] \[ \text{if } M_{ex} \leq 0.5 M_{ylx} \] \[ \text{[25]} \]

where \( M_{ex} \) is the elastic lateral-torsional buckling of the angle bent about the x-axis. It is defined as:

\[ M_{ex} = C_{b} r_{0} A \sqrt{f_{y} f_{t}} \] \[ \text{[26]} \]

\( C_{b} \), in Eq. 26, is a coefficient whose value depends on the moment gradient. For members subjected to uniform bending moment \( C_{b} \) is equal to unity.

\( M_{ylx} \) is the moment causing initial yielding at the extreme compression fiber. It is computed as follows:

\[ M_{ylx} = S_{xc} F_{y} \] \[ \text{[27]} \]

where \( S_{xc} \) is the compression section modulus about the x-axis.

\( \Omega_{f} \) is the factor of safety for bending which is assumed to be equal to 1.67. The ultimate capacity of a single angle can be computed using Eq. 1 with a factor of safety equal to unity.

**Allowable bending moment \( M_{ay} \)**

The allowable bending moment about the y-axis is computed as follows:

\[ M_{ay} = \frac{M_{ny}}{\Omega_{f}} \] \[ \text{[28]} \]

where \( M_{ny} \) is the critical lateral-torsional buckling moment defined as:

\[ M_{ny} = M_{yly} \left( 1 - \frac{M_{ylx}}{4M_{ey}} \right) \] \[ \text{if } M_{ey} > 0.5 M_{ylx} \] \[ \text{[29]} \]
where $M_{ey}$ is the elastic lateral-torsional buckling of the angle bent about the y-axis. It is defined as:

$$
M_{ey} = C_s A f_x \left[ \beta + C_s \sqrt{\beta^2 + r_0^2 \left( f_t/f_x \right)} \right] / C_{my}
$$

where

- $C_s = +1$ for moment causing compression on the shear centre of the centroid.
- $C_s = -1$ for moment causing tension on the shear centre of the centroid.

$$
\beta = \frac{1}{2 I_y} \left[ \int_A x^3 \, dA + \int_A x y^2 \, dA \right] - x_0
$$

$I_y$ = moment of inertia about the $y$-axis.

The ratio between the measured ultimate loads of the tested angles and the ultimate capacity computed according to the American Specifications (AISI 1986) is shown in Fig. 19(a) and 19(b). When the yield stress 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(a). However, when the yield stress 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.

These results indicate that the American Specification underestimated the ultimate capacity of the angles. For both galvanized and ungalvanized angles this underestimation ranged 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 on the behaviour of galvanized and ungalvanized cold-formed steel angles. The specific objectives were to study the influence of temperature, cold work, galvanization, and type of end connection 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. Equal number 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 tensile coupon tests conducted at the same temperatures range.

Based on the results of this experimental program the main findings can be summarized as follows:

1. The average yield strength of galvanized flat coupons was approximately 9% higher than ungalvanized flat coupons tested at room temperature and 5% higher at subfreezing temperatures.

2. There was only a 2% difference between the yield strength of galvanized corner coupons and that of ungalvanized corner coupons at room temperature and there was no difference at subfreezing temperatures.

3. There was no difference between the average ultimate strength of galvanized and ungalvanized flat or corner coupons at all temperature levels.

4. 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.

5. 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.
(6) The average yield strength of the ungalvanized flats tested at room temperature was approximately 38% higher than the yield strength of the virgin metal as specified by the supplier.

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

(8) The average ultimate strength of both galvanized and ungalvanized corner coupons are approximately 7% higher than that of flat coupons at all temperature levels.

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

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

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

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

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

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

(15) The method used to connect the angles at the supports has a marked effect on their behaviour and their load bearing capacity. Since the attachment is through one leg, single angles behave as beam-columns rather than concentrically loaded columns.
(16) The ultimate load for the galvanized angles computed according to CSA-S136-M84 was between 13% and 28% higher than the measured loads when the yield strength obtained from standard coupon tests was used, and between 0% and 14% higher when the yield strength specified by the supplier was used. For the ungalvanized angles, the computed ultimate load was between 16% and 31% higher than the measured loads when the yield strength obtained from the coupons was used and between 0% and 14% higher when the specified yield strength was used. These results indicate that the current Canadian Specification is unconservative since the computed ultimate loads exceed the measured loads.

(17) The American Specification overestimated 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 Canadian Specification for the design of single angles should be revised and made more conservative to reflect a more realistic member behaviour. It is recommended that single angles be designed as beam columns.

The experimental program discussed in this paper dealt with equal leg angles not subject to local buckling. Further research is required to investigate the effect of local buckling on the ultimate capacity of angles, as well as, to establish design guidelines for unsymmetrical angles. Additional research is also required to examine the effect of galvanization, cold work, and temperature on the behaviour of thicker angles.

ACKNOWLEDGEMENT

The project described in this paper was sponsored by Manitoba Hydro, Winnipeg, Manitoba, Canada. The technical assistance provided by Mr. P. Charvarnichborikarn, Mr. E. Lemke and M. McVey is gratefully acknowledged. The authors would also like to acknowledge the technical advice provided by Mr. C. Wong, Senior Engineer with Manitoba Hydro.
APPENDIX I.-REFERENCES


Canadian Standard Association, "Cold-Formed Steel Structural Members - CAN3-S136-M84," 1984.

Karren, K.W., "Corner-properties of Cold-Formed Steel Shapes", Journal of Structural Division, ASCE, Vol. 93, No. ST1, 1967.

APPENDIX II.-NOTATION

The following symbols are used in this paper:

- \( A \) = cross sectional area
- \( b \) = outstanding width of the larger leg
- \( C \) = ratio of corner area to total cross sectional area
- \( C_m \) = moment gradient coefficient
- \( C_r \) = factored compressive resistance
- \( (C_r)_{\text{max}} \) = maximum compressive resistance
- \( C_w \) = warping constant
- \( D \) = number of 90° corners in a section
- \( E \) = modulus of elasticity
- \( f, F_a, f_{cr}, F_p \) = critical buckling stress
- \( (f_{cr})_{\text{elastic}} \) = elastic critical buckling stress
- \( (f_{cr})_{\text{inelastic}} \) = inelastic critical buckling stress
- \( f_p \) = proportional limit of stress
- \( f_r \) = residual stress
- \( F_y, F_{ya}, F_y' \) = yield stress
- \( F_{yc} \) = yield stress of corners
- \( F_{yf} \) = yield stress of flats
- \( G \) = shear modulus of elasticity
- \( J \) = St. Venant's torsion constant
- \( K \) = effective length factor
- \( L \) = unbraced length
- \( M \) = applied bending moment
- \( M_a \) = allowable bending moment
- \( P \) = applied axial load
\[\begin{align*}
\text{\(P_a\)} & = \text{allowable axial load} \\
\text{\(P_{cr}\)} & = \text{buckling load} \\
\text{\(P_n\)} & = \text{ultimate axial load} \\
\text{\(r\)} & = \text{radius of gyration} \\
\text{\(S\)} & = \text{section modulus} \\
\text{\(t\)} & = \text{thickness of section} \\
\text{\(W\)} & = \text{ratio of centerline length of the entire section-to-thickness} \\
\text{\(x\)} & = \text{principal axis} \\
\text{\(x_0\)} & = \text{distance between shear centre and centroid long the \(x\)-axis} \\
\text{\(y\)} & = \text{principal axis} \\
\text{\(\phi_a\)} & = \text{resistance factor} \\
\text{\(\Omega\)} & = \text{safety factor}
\end{align*}\]
Table 1. Summary of Results from Angles Tests

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Table 2(a). Summary of Results from Flat Tension Coupon Tests

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Table 2(b). Summary of Results from Corner Tension Coupon Tests

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Fig. 1 Refrigeration unit and test set-up
(Numbers in brackets refer to galvanized sections)

(a) Average cross-sectional dimensions  
(b) Location of standard coupons

Fig. 2 Average dimensions and location of standard coupons
(a) Double knife edge support

(b) Modified end support without knife edges

Fig. 3 End supports used in the experimental program
Fig. 4 Refrigeration unit for testing tension coupons
Fig. 5 Yield Strength of flat Coupons as Function of Temperature
Fig. 6 Yield Strength of Corner Coupons as Function of Temperature
Fig. 7 Ultimate Strength of Flat Coupons as Function of Temperature
Fig. 8 Ultimate Strength of Corner Coupons as Function of Temperature
Fig. 9 Yield Stress of Ungalvanized Tension Coupons as Function of Temperature
Fig. 10 Yield Stress of Galvanized Tension Coupons as Function of Temperature
Fig. 11 Ultimate Strength of Galvanized Tension Coupons as Function of Temperature
Fig. 12 Ultimate Strength of Ungalvanized Tension Coupons as Function of Temperature
Fig. 13 Angle specimen at failure
Fig. 14 Column curves for concentrically applied load

(a) Galvanized angles

(b) Ungalvanized angles

A: \( F_y = 300 \text{ MPa} \)

B: \( F_y = 414 \text{ MPa} \)

C: \( F_y = 430 \text{ MPa} \)

\( \Delta \): Current test results
Fig. 15 Effect of temperature on the behaviour of galvanized and ungalvanized angles.
Fig. 16 Effect of end supports on the behaviour of angles

A: 1 Bolt. With knife edges.
B: 1 Bolt. Without knife edges.
Fig. 17. Compressive resistance of galvanized angles according to CSA-S136-M84
Factored Compressive Resistance

(a) Using specified yield strength

Unfactored Compressive Resistance

Factored Compressive Resistance

(b) Using yield strength obtained through standard coupon test.

Fig. 18. Compressive resistance of ungalvanized angles according to CSA-S136-M84
Fig. 19 Ratio of measured to computed load according to AISI

(a) Using yield strength obtained through standard coupon tests

(b) Using specified yield strength
February 28, 1989

Professor Elwi
Department of Civil Engineering
University of Alberta
Room 220 Civil-Electrical Bldg.
Edmonton, Alberta
T6G 2T7

Dear Professor Elwi:

Please find enclosed the paper entitled "Behaviour and Design of Cold-Formed Steel Angles" for presentation at the Structural Engineering Conference in Cairo. I would appreciate it if you could send me any information related to this conference that you may have.

Looking forward to meeting you in Egypt.

Sincerely,

Dimos Polyzois
Associate Professor

DP/jp
Encl.