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Mechanical Properties and Bond Behaviour of Ransome Bars

Michael R. Knight[1] and Lisa R. Feldman[2]
[1]B.Sc. Student, Department of Civil & Geological Engineering, University of Saskatchewan, Saskatoon, SK, S7N 5A9
[2] Associate Professor, Department of Civil & Geological Engineering, University of Saskatchewan, Saskatoon, SK, S7N 5A9

Abstract: Six splice specimens were subjected to four-point loading to evaluate the bond performance, including casting position, of square twisted (i.e. Ransome) steel reinforcement that may be found in historical concrete construction. The longitudinal reinforcement used in all specimens had a nominal side face dimension of 25.4 mm and lap splice lengths ranged from 410 to 610 mm (i.e. 16.1 to 24.0 times the bar size). The bars were recreated with their pitch established from the existing literature and from measurements of reinforcement in historical concrete structures. All specimens failed due to bond loss between the longitudinal reinforcement and the surrounding concrete. Results of the subsequent data analysis suggest that Ransome bars are slightly more sensitive to casting position, and are approximately 48% more effective in bond as compared to plain square bars.

1 Introduction

Figure 1 shows that, in addition to plain steel bars, proprietary systems of corrugated, deformed, and twisted bars were used as reinforcement at the beginning of the twentieth century (Loov 1991). Square twisted reinforcing bars, shown in Figure 1(h), were patented by Ernest L. Ransome in 1884 (Hurd 1996). Ransome's objective in twisting plain square bars was to develop a method of achieving continuous bond along the length of a reinforcing bar rather than relying on mechanical end anchorages to transfer forces between the concrete and the reinforcement. Ransome had initially been criticized for seriously injuring the bars by twisting them, then accused of doctoring the results of his tests to show that their behaviour was superior to plain bars, until, finally, his bars were accepted and widely used as reinforcement for concrete construction (Hurd 1996). Many historically significant concrete structures in Western Canada including the Peter MacKinnon Building (formerly known as the College Building) on the University of Saskatchewan campus, the Centre Street Bridge in Calgary, Alberta, and the Hillhurst (Louise) Bridge in Calgary, Alberta, were reinforced with these bars. Many of these structures have now reached an age where they have undergone or require rehabilitation.

Square twisted (i.e. Ransome) bars do not conform to CSA Standard G30.18 (CSA 2009a), in part due to the cold working required to twist the bars (Shuman 1907). As a result, current editions Canadian and American codes that address reinforced concrete design (e.g. CSA 2004, CSA 2006, AASHTO 2012, ACI 318 2011) do not provide information related to the development and splice lengths required for these bars. Practicing engineers therefore have little guidance when charged with the evaluation of concrete structures reinforced with these bars.

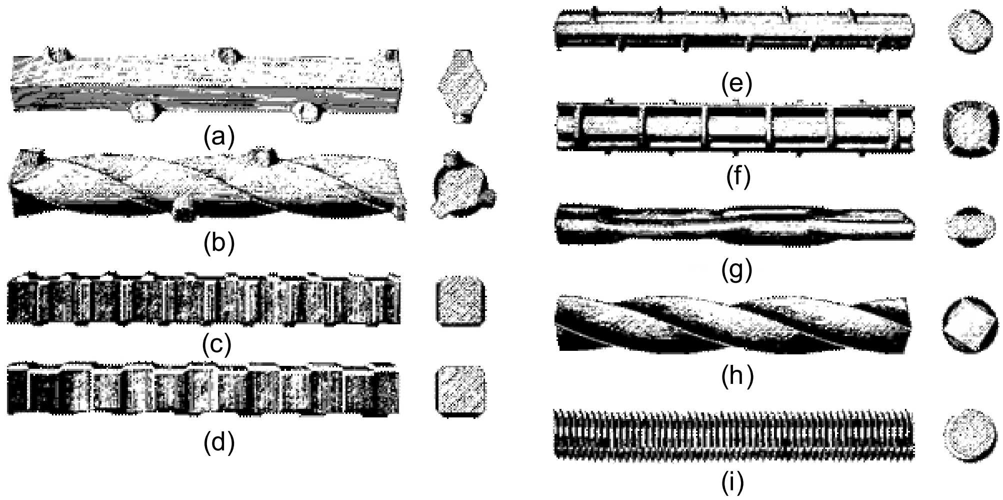

Figure 1: Historical Reinforcing Bar Types (after Abrams 1913): (a) Lug Bar – Straight, (b) Lug Bar – Twisted, (c) Corrugated Square (Type A), (d) Corrugated Square (Type B), (e) Corrugated Round (Type C), (f) Cup Bar, (g) Thatcher Bar, (h) Square Twisted (Ransome) Bar, and (i) Round Bar with Standard Threads.

This paper presents the results of a preliminary experimental investigation to determine the mechanical properties and bond behaviour of Ransome bars. The bars were recreated, with their pitch (i.e. length per full bar revolution) established from data identified in the existing literature, and confirmed based on an inspection of samples of these bars. Initial results and a preliminary analysis of the test data are reported.

2 Experimental Program

The description of the specimens and test setup are similar to those reported by Hassan and Feldman (2012) and Sekulovic MacLean and Feldman (2012). Figure 2 shows the cross-section, elevation, and plan view for the six specimens included in this investigation. All of the specimens had identical cross-sectional dimensions and span lengths. Figures 2(a) and (b) show the cross-section of specimens with Ransome bars cast in the bottom and top positions, respectively. The reinforcement ratio for all specimens, A_s/bd, was 1.26%. Specimens cast with the reinforcement in the top position were inverted prior to testing such that Figure 2(c) shows the elevation of all specimens as tested, including the span length, loading, and reinforcement arrangement. The shear span to depth ratio, a/d, was approximately 3.94 for all specimens. Figure 2(d) shows a plan view of the specimens and illustrates the arrangement of the spliced longitudinal bars. All specimens were designed to fail in bond and had lap splice lengths, L_s, ranging from 16.1 to 24.0 times the bar size, which, for the case of square twisted bars, is defined as the bar side face dimension. Figure 2(c) shows that a vertical load was applied via a single actuator using a spreader beam with a self-weight that exerted a load P of 1.77 kN on the specimen to establish the four-point loading arrangement. Loading was applied at a rate of 0.0015 mm/s to failure.

2.1 Concrete

The concrete had a target compressive strength of 20 MPa. General purpose (Type GU) Portland cement was used without admixtures or air entrainment. The mix design consisted of a carbonate, gneiss, and granite coarse aggregate blend from the Watrous pit in Saskatoon, and a washed silica sand fine aggregate from the Wakaw pit, SK. The mix design, per m^3 of concrete, was: 270 kg cement, 993 kg sand, 1040 kg crushed coarse aggregate, and 145 L water. The maximum aggregate size was 20 mm, and all aggregates conformed to CAN/CSA A23.1-09 (2009b).

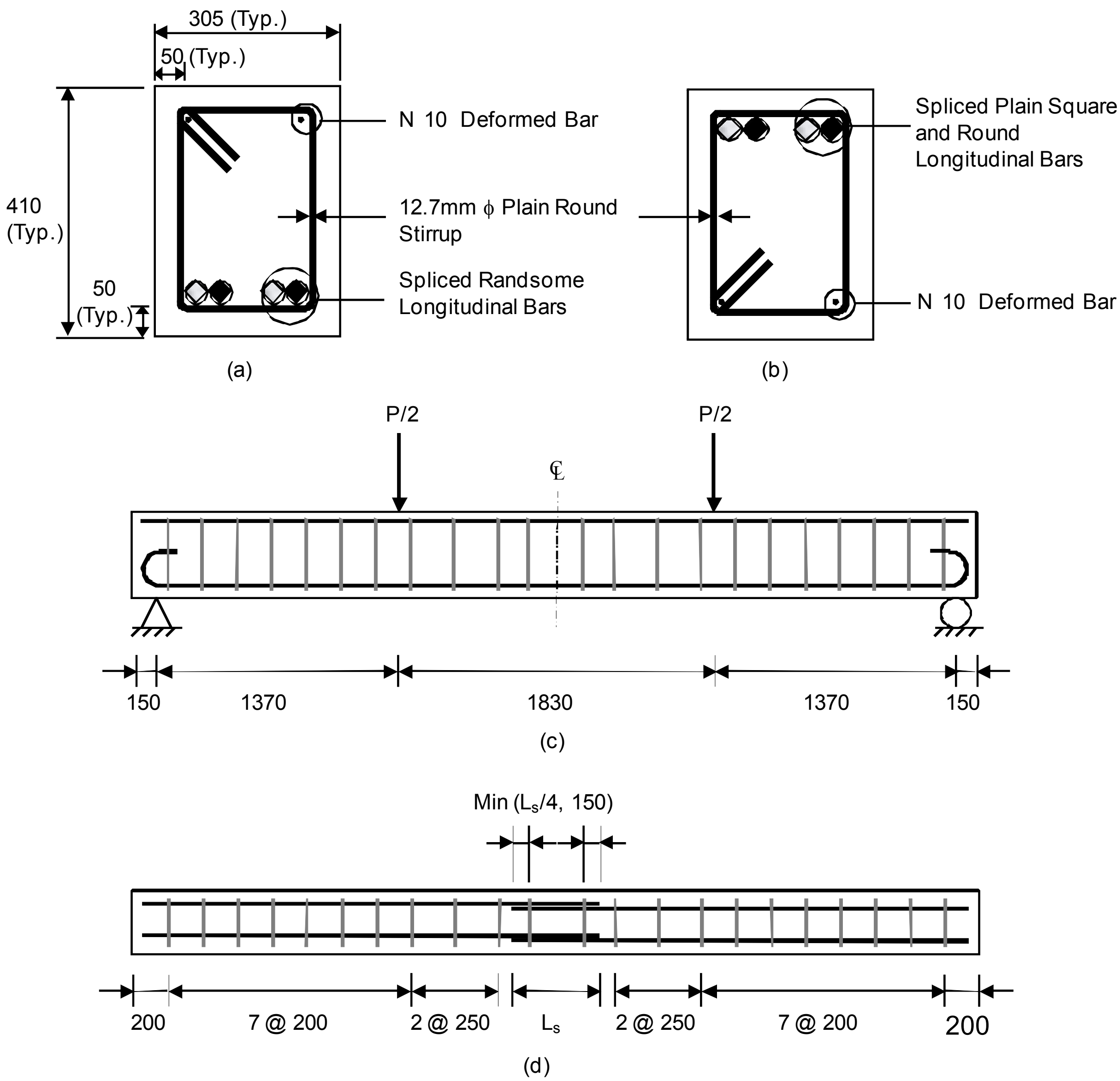

Figure 2: Splice Specimen Geometry: (a) Cross-Section for Specimens with Bottom Cast Reinforcement, (b) Cross-Section for Specimens with Top Cast Reinforcement, (c) Elevation, and (d) Plan View.

Table 1 shows the concrete compressive strength of the specimens at the time of testing as established from the results of companion concrete cylinders stored under the same conditions and tested on the same day as the corresponding splice specimen. Specimens were moist cured using wet burlap and plastic sheets for 7 days following casting and were then stored in the laboratory until testing.

2.2 Reinforcement

All principle longitudinal reinforcement was 25.4 mm (1 in.) square hot rolled CSA G40.21 300W steel and was procured from a single heat batch. The longitudinal material properties for the as-received plain bar stock were established from six coupons obtained and machined from surplus bar lengths and tested in accordance with ASTM A370-97a (1997). The average dynamic yield strength, f_{yd}, was 350 MPa, and the average ultimate strength, f_u, was 538 MPa.

The pitch (i.e. the length per twist or bar revolution) of the bar will affect its bond performance and therefore needed to be carefully selected to ensure that it matched that typical for historical Ransome bars. This was achieved by a careful review of the available literature and an inspection of existing historical structures. Table 2 shows the wide range of the pitch, in terms of the number of turns per foot, used for different bar sizes as reported by various sources (Ransome 1894; Shuman 1907; Hool & Johnson 1918; Felder, CRSI, personal communications, 2012). The pitch was intentionally selected to ensure that the resulting increase in the yield strength of the bar remained less than the ultimate strength and so was a function of the type of steel used. The values of pitch as shown in Table 2 as reported by Shuman (1907) were reported to increase the yield strength of the reinforcement between 52.6 and 117% and the ultimate strength of the reinforcement between 17.5 and 51% (Shuman 1907).

The pitch of Ransome bars used to reinforce two historical structures was also measured. Four Ransome bars found in the Peter MacKinnon Building (formerly the College Building) on the University of Saskatchewan campus were accessible via concrete ports created during its 2005 inspection and rehabilitation. The pitch of three 1/2 inch (12.7 mm) bars used to reinforce the main floor slab had a pitch that ranged from 5.7 to 6.3 in. (145 to 160 mm) per full revolution (i.e. 1.90 to 2.35 turns per foot), while a ¾ in. (19 mm) bar used as longitudinal reinforcement in a column supporting the main floor of the building had a measured pitch of 12 in. (305 mm), equivalent to 1 turn per foot. Figure 3 shows a photograph of one of the measured ½ in. Ransome bars cast in the main floor slab. The same pitch (i.e. 1 turn per foot) was noted for a ¾ in. (19 mm bar) that was removed from the Hillhurst (Louise) Bridge located in Calgary, Alberta, originally constructed in 1921, during its 1996 rehabilitation. Measurements of all bars generally fall within the range reported in the available literature.

The pitch selected for the 1 in. (25 mm) bars used in the current investigation was 12 in. (305 mm) or one turn per foot to match the values provided in the literature. The bars were twisted using a lathe (Figure 4), with the spindle at the headstock free to rotate, and the tailstock fixed by securing the locking mechanism. Figure 5 shows that a 600 mm length at one end of each bar was intentionally left untwisted to allow these segments to remain sufficiently ductile for bending into a standard 180 degree hook located adjacent to the beam supports as shown in Figure 2(c) (bend diameter = 200 mm, straight bar extension = 100 mm) by a local reinforcing bar supplier to ensure that the bond failure would occur within the lap splice length.

Table 1: Summary of the Experimental Program

Specimen ID[1]	Age at Test (days)	Measured f'_c (MPa)	Measured R_y (μm)	Normalized Maximum Attained Load $P_{max}/\sqrt{f'_c}$ (kN/$\sqrt{\text{MPa}}$)
25☒-410↓	65	20.9	9.22	23.6
25☒-510↓	64	20.2	9.27	29.4
25☒-610↓	64	18.2	9.65	37.5
25☒-410↑	54	21.6	9.47	15.0
25☒-510↑	62	19.9	9.42	14.4
25☒-610↑	63	19.7	9.92	19.7

[1]The specimen designation consists of two numbers and associated symbols separated by a hyphen. The first number represents the longitudinal bar size (i.e. side face dimension) in mm, with the symbol that follows (☒) confirming that the longitudinal reinforcement in the specimen consisted of Ransome bars. The second number, following the hyphen, denotes the lap splice length in mm, and the final symbol indicates whether the reinforcement was cast in the top (↑) or bottom (↓) position.

Challenges existed in obtaining the stress versus strain relationship and material properties for the fabricated Ransome bars as the Universal Testing machine (UTM) used was not capable of gripping the twisted bars. Figure 6 shows that full penetration welds between short lengths of 32 mm square untwisted bar segments at the top and bottom of the Ransome bar specimen to be tested were made to ensure that the specimen could be gripped by the testing machine. Two small plates located 25 mm apart were tack welded to the Ransome bar to allow two linear variable differential transducers (LVDTs) to measure strain, independent of any increased deformation caused by the full penetration welds, as a function of the applied load as recorded by the UTM. Furthermore, the resulting strain values resulted from a combination of tensile deformation and untwisting of the bars and could not be uncoupled. Results do, however, suggest that twisting the bars eliminates their yield plateau. The ultimate stress, f_u, caused by failure of one the full penetration welds, was 589 MPa. Additional tensile testing is planned using a modified arrangement that will ensure that the true ultimate stress of the Ransome bar is achieved.

Table 2: Pitch of Ransome Bars (in turns per foot)

Bar Size (in.)	Pitch (Ransome 1894)	Pitch (Shuman 1907)	Pitch (Hool & Johnson 1918)	Pitch (Felder)[1]
¼ x ¼	6	4	5	5
½ x ½	3	3 - 5	2	2-3
¾ x ¾	2	1 ½ - 2 ½	1	1
1 x 1	0.75	1 – 1 ¾	¾	¾ - 1
1 ¼ x 1 ¼	n/a	¾ - 1 ½	½	½

[1]A. Felder, Technical Director, Concrete Reinforcing Steel Institute (personal communications, 2012)

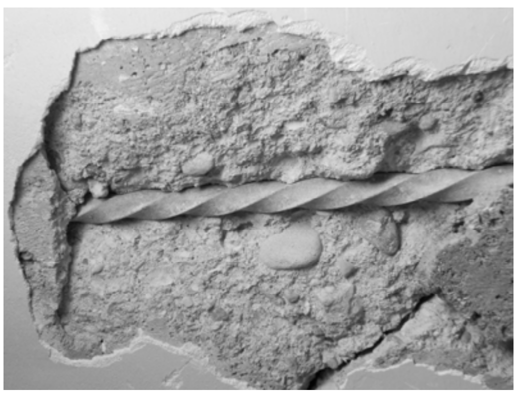

Figure 3: Ransome Bar Reinforcing Main Floor Slab in the Peter MacKinnon Building, University of Saskatchewan Campus.

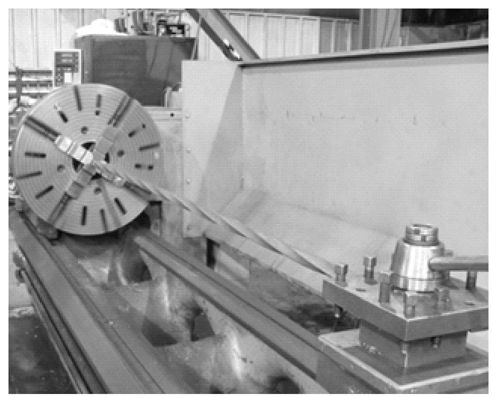

Figure 4: Twisting of the Ransome Bars (photo courtesy RMD Engineering Inc.)

Following twisting, the longitudinal bars were sandblasted using 200 grit aluminum oxide, a nozzle distance of 125 mm, and a 698 kPa blast pressure to make them more representative of historical bars (Feldman & Bartlett 2005). The surface roughness of each bar was characterized by the maximum height of profile, R_y, calculated as the distance between the highest peak and deepest valley on the bar surface (Mitutoyo 2006). A total of 16 roughness measurements were made on each bar using a surface roughness tester and a single 0.25 mm stroke. The average combined R_y value for all longitudinal bars was 9.49 μm. Results of previous work (Feldman & Bartlett 2005) suggest that this is a lower-bound estimate of the roughness of historical plain reinforcement.

The shear reinforcement consisted of 12.7 mm diameter hot rolled CSA G40.21 300W plain steel bars spaced at 200 mm on centre within the shear spans and 250 mm on centre within the constant moment region outside of the lap splice length (Figure 2(d)). Two additional stirrups were placed in the splice region one-quarter of the splice length, but not exceeding 150 mm from the ends of the splice, to prevent prying action of the longitudinal reinforcement. The specimens had considerably more shear

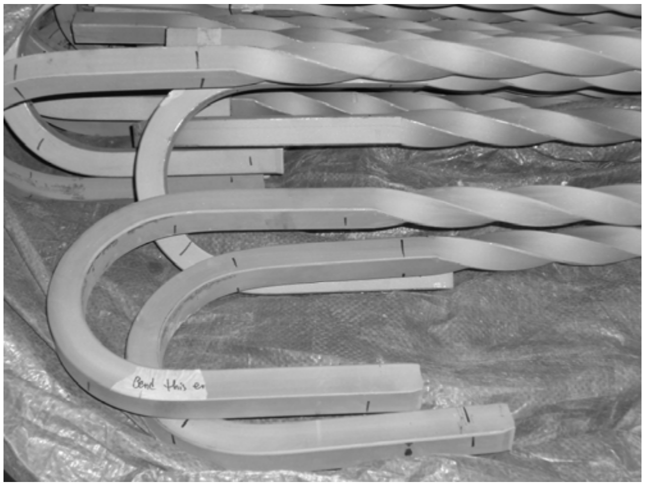

Figure 5: Hooks on Ransome Bars

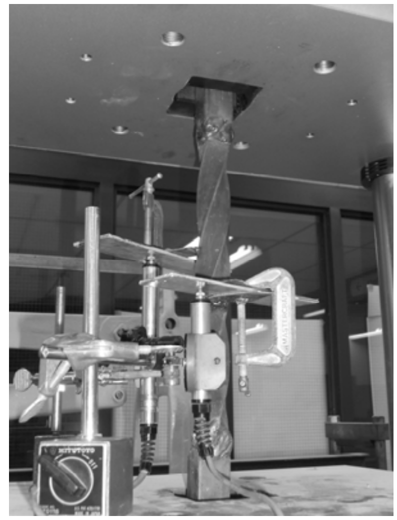

Figure 6: Tensile Testing of a Ransome Bar

reinforcement than strictly necessary to ensure that failure would be governed by bond between the longitudinal reinforcement and the surrounding concrete.

3 Test Results

Table 1 shows the observed maximum loads attained by the specimens. All reported loads have been normalized by the square root of the concrete compressive strength given that this is consistent with previous equations for deformed bars.

As per specimens reinforced with plain square bars reported elsewhere (Sekulovic MacLean & Feldman 2012), an examination of the lap spliced reinforcing bars following concrete removal after testing was completed showed that pullout of the reinforcement occurred for all specimens (Figure 7). Splitting cracks were not evident in the specimens even though the twisted configuration of the Ransome bars effectively creates deformations which induce radial stresses in the surrounding concrete.

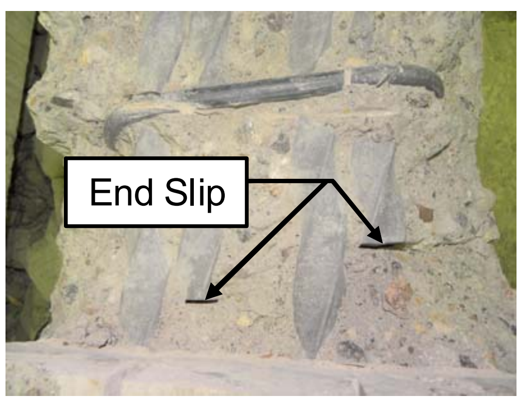

Figure 7: Evidence of Bar Slip Following Concrete Removal for Specimen 25☒-410↓

3.1 Comparison with Plain Bars

Figure 8 shows the ratio of the maximum normalized load for specimens longitudinally reinforced with Ransome bars, $(P_{max}/\sqrt{f'_c})$☒, to those reported for specimens longitudinally reinforced with plain square bars, $(P_{max}/\sqrt{f'_c})$■ as previously reported by Sekulovic MacLean and Feldman (2012). The ratios were calculated for pairs of specimens longitudinally reinforced with bars of the same size and lap splice lengths. The resulting ratios of $(P_{max}/\sqrt{f'_c})$☒/ $(P_{max}/\sqrt{f'_c})$■ ranged from 1.29 to 1.67, with an average value of 1.48, and so suggests that plain square bars are approximately 67% as effective in bond as Ransome bars. A similar comparison of specimens longitudinally reinforced with plain round and modern deformed bars with the same nominal diameter was conducted by Hassan and Feldman (2012) and showed that plain bars are capable of resisting loads that are approximately 60% of those recorded for similar specimens reinforced with modern deformed bars. Though both investigations included a limited number of specimens, they do indicate that the bond performance of Ransome bars approaches that of modern deformed bars.

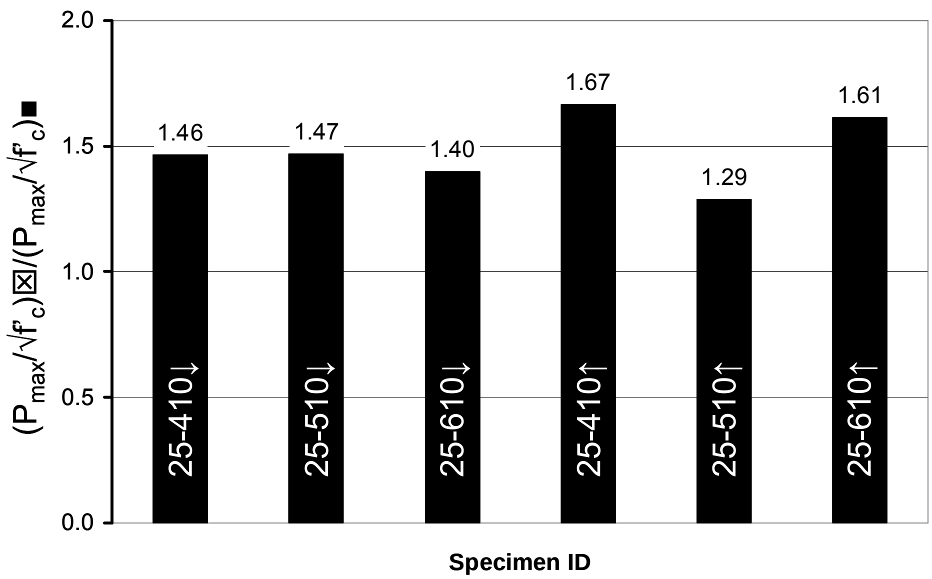

Figure 8: Ratio of the Normalized Loads for Pairs of Specimens Longitudinally Reinforced with Ransome versus Plain Square Bars

Figure 8 further shows that the scatter of $(P_{max}/\sqrt{f'_c})$☒/$(P_{max}/\sqrt{f'_c})$■ is significantly greater for specimens in which the longitudinal reinforcement is cast in the top position as compared to those cast in the bottom position and is attributed to the sensitivity of concrete consolidation surrounding top cast reinforcement.

3.2 Bar Casting Position

Figure 9 shows the ratio of the maximum normalized applied loads for each pair of specimens reinforced with Ransome bars with the same lap splice length, but with this reinforcement cast in the top position for one specimen, and in the bottom position for the other specimen (i.e. $(P_{max}/\sqrt{f'_c})\uparrow/(P_{max}/\sqrt{f'_c})\downarrow$). Figure 9 shows that all specimens with top cast reinforcement failed at loads well below those for bottom cast reinforcement, with a resulting average ratio of the normalized maximum loads equal to 0.55. In contrast, current American (ACI 2011) and Canadian (CSA 2004) code provisions for reinforced concrete require a 30% increase in development length for modern deformed bars cast in the top position, and the CEB-FIP Model Code (CEB-FIP 1993) provides a multiplier of 0.7 for the average bond stress in such cases. Sekulovic MacLean and Feldman (2012) suggested a top cast factor of 0.6 for plain square bars based upon the results of their recent investigation. Ransome bars are therefore more sensitive to casting position than modern deformed bars and appear to be similarly, but perhaps slightly more sensitive, to casting position than plain square bars. The slight difference in recommended top cast factors for plain square and Ransome bars may be attributed to differences in the shape of the voids that form beneath these two bar types. The bottom face only will be affected by voids that form beneath top cast plain square bars assuming that they have been placed perfectly square within the reinforcing cage. Voids forming below Ransome bars will affect two bar faces to varying degrees along the length of such bars due to their twisted configuration.

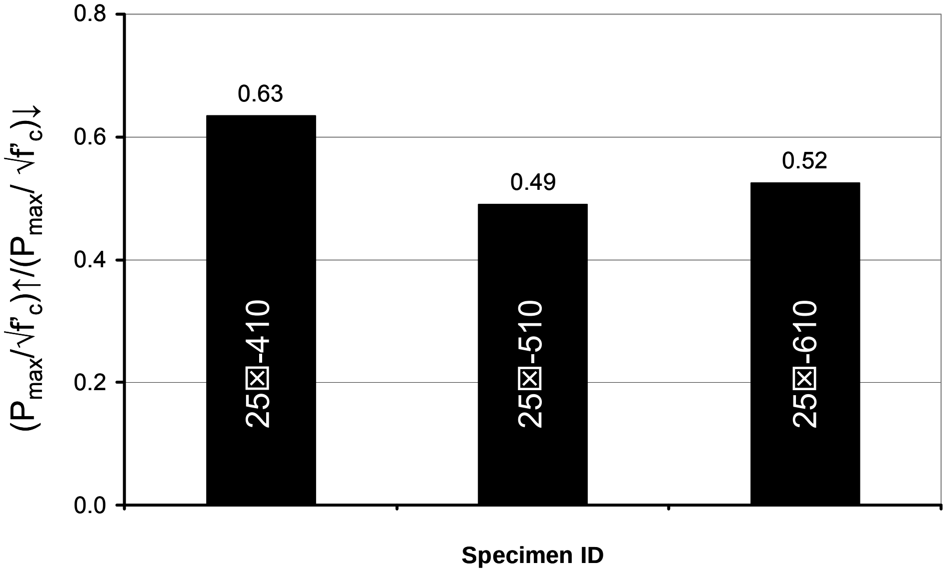

Figure 9: Ratio of the Normalized Maximum Loads for Pairs of Specimens with the Longitudinal Reinforcement Cast in the Top and Bottom Position

4 Summary and Conclusions

This paper presents the results of a limited experimental investigation consisting of six splice specimens reinforced with Ransome (i.e. square twisted) bars that were subjected to four-point loading. The Ransome reinforcing bars were recreated with a pitch of one turn per foot to match the values reported in the available literature and as measured in historical concrete structures. Specimens were either cast with the longitudinal reinforcement in the bottom or top position, and were 305 mm wide by 410 mm tall, with span lengths of 4570 mm. The side face dimension of the longitudinal reinforcement in all specimens was nominally 25.4 mm. Lap splice lengths varied from 16.1 to 24.0 times the side face dimensions of the longitudinal bars. The following significant conclusions are noted:

1. All specimens failed due to bond loss between the longitudinal reinforcement and the surrounding concrete.
2. Plain bars are approximately 67 and 60% as effective in bond as Ransome and modern deformed bars, respectively. It can therefore be inferred that the bond performance of Ransome bars approaches that of modern deformed bars.
3. Ransome bars are slightly more sensitive to casting position than plain square bars, with a recommended top cast factor of 0.56. This factor is lower than that used for deformed bars in Canadian, American, and European concrete codes.
4. A wide range of bar pitch (i.e. turns per foot) is reported in the literature. Additional testing should be conducted to evaluate the influence of bar pitch on bond performance.

Acknowledgements

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