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Self-drilling Screwed Knee-joints for Cold-formed Steel Portal Frames in Cyclonic Regions

John Carr[1], Andrew Mansour[2] and Julie Mills[3]

Abstract

Current knee joint design practices for cold-formed steel portal frames have traditionally adopted techniques used in hot-rolled steel joint design. Previous investigations conducted at the University of South Australia have shown the inadequacy of this practice and led to the development of a self-drilling screw joint alternative that is capable of carrying significantly higher moments than conventional designs. This study aimed to investigate the suitability of the self-drilling screwed knee joint in cyclonic regions, as well as conducting a preliminary assessment of the suitability of other joints currently used for such sheds in cyclonic regions. In addition, a new test method was developed that was more economic than past testing and more easily adaptable to test a range of section sizes and joint configurations. Test results both validated the new test method through comparison with previous testing, and showed the suitability of the self-drilling screwed joint for the higher moments required in frames subjected to cyclonic conditions.

Introduction

Current design practices used in the construction and fabrication of knee-joints for cold-formed steel portal frames have generally adopted techniques popularly used for joints connecting hot-rolled steel sections (e.g. simple side butt joint). Previous investigations (Mills 2000) have shown that the tested capacity of knee-joints connecting cold-formed sections using hot-rolled joint designs was

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significantly lower than theoretically expected due to local buckling failure caused by the highly concentrated load on the inside flange of the column, together with the high depth: thickness ratio of cold-formed sections.

Over recent years, the University of South Australia has successfully developed a self-drilling screwed knee-joint prototype for use in portal frames in non-cyclonic regions (Mills & Miller 2001, Mills & LaBoube 2004). Studies have determined that this joint prototype, constructed using back-to-back cold-formed C-sections was able to carry a significantly higher moment capacity than a conventional joint design.

This study investigated the suitability of using the self-drilling screwed knee-joint prototype in portal framed buildings in cyclonic regions. In addition, an improved method of testing the knee-joint prototype, to ensure that joints are subject to a constant ratio of combined bending and axial loads when using a range of member sizes in the testing machine, has also been developed. It is hoped that the outcomes of this study will provide further options for industry to consider in the design and testing of knee-joints for cold-formed steel portal frames.

Survey of shed manufacturers & suppliers

In order to gain an insight into current knee-joint design practices and typical shed parameters adopted in Australian cyclonic regions, a questionnaire was forwarded to randomly selected shed manufacturers and suppliers based in Northern Queensland, Northern Western Australia and the Northern Territory. The main finding are summarised as follows:

Shed spans typically ranged from 16ft to 59ft (5 – 18m) in conjunction with bay lengths of 10ft to 20ft (3 to 6 m). Cold-formed section sizes used in construction varied from single C15015 lengths to C30024 members, with the practice of combined members (i.e. back-to-back) proving common for spans greater than 39ft (12m). In higher design wind speed regions (i.e. Northern W.A.), hot-rolled steel was the preferred design option, particularly for spans greater than 20ft (6m).

A variety of knee-joint designs are currently being used in industry, although most utilise a bolted connection of some nature, with added strength provided by way of a gusset plate, brace/bracket and/or sleeve. The conventional side-butt joint also featured in the array of joint designs used. Whilst all participants indicated that no testing methods were used by their business to assess joint capacities, all were satisfied with the performance of their respective joint designs. Many were also aware of the concept of using self-drilling screws as a joint fixity medium, however the idea was generally perceived to be inferior in some way.

The survey confirmed the relevance of this study to industry by confirming firstly, that cold-formed steel is in fact used in construction in these higher wind prone areas, and secondly, the familiarity of self-drilling screwed joints within industry, notwithstanding the fact that the method does not appear to be widely used or favoured.

Wind load analysis

From the results of the survey, a typical shed size (19.6ft (6m) span × 9.8ft (3m) bays) was selected for computer modelling and analysis. The aim of this exercise was to identify critical cases for opening and closing moments at the knee-joint and to determine the required joint capacities in order to withstand cyclonic and non-cyclonic wind loadings. The results of the wind load analysis with respect to the bending moment generated at the knee of the portal frame are summarised in Table 1. The analysis showed that a self-drilling screwed knee-joint must be capable of withstanding design bending moments of at least 148 kip in (16.7kNm) in order to be considered a suitable design option for cyclonic regions.

Table 1 Design wind moments for typical6m span shed, cyclonic and non-cyclonic regions

Australian wind Region & Terrain Category	**Design wind speed mph (m/s)**	**Knee-joint Bending Moment (kip in, kNm)**	
		Uplift (opening)	**Downwards (closing)**
A3	85 (38)	72.0 (8.14)	31.1 (3.51)
C3	121 (54)	148 (16.7)	57.0 (6.44)
C1	136 (61)	189 (21.4)	71.8 (8.11)
D3	150 (67)	228 (25.8)	84.7 (9.57)
D1	172 (77)	303 (34.2)	111 (12.5)

Design of the test apparatus

Previous tests had been conducted using a conventional tensile/compression testing machine (refer Mills & Miller 2001 for details). However, this placed limitations on the size of section that could be tested, and required a fairly time consuming set-up, with different end jugs needing to be fabricated for various joint types. This study designed a new test apparatus that was simpler and quicker to use as well as being adaptable to different joint designs. The final design is pictured in Figure 1.

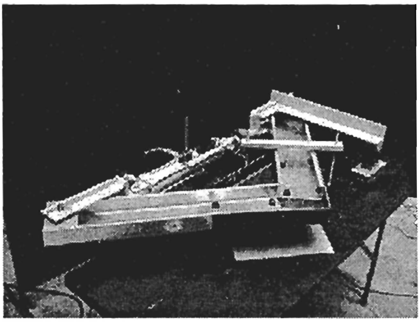

Figure 1 Final design of test apparatus

The apparatus design used a double-acting hydraulic ram to enable testing for opening and closing moments. Members were positioned horizontally within the apparatus and roller supports were used to enable the joint to open or close freely within the apparatus. Apparatus geometry was primarily based on the distance between the end-connection pinholes, which was set with the piston in the hydraulic ram positioned at half its stroke in order to allow for the testing of “opening” and “closing” cases. This distance was also determined for the purpose of maintaining a constant “moment arm” (between the points of rotation of the joint and the line of the applied load) for a range of specimen section sizes. In addition, the apparatus was designed to be able to test a variety of joint configurations (eg. back-to-back, self-drilling screwed; side-butt; gusset plate; etc).

With the aid of plate stiffeners, the end-connections were designed to exceed the anticipated maximum compressive load during testing. The end-connections were also chamfered to allow additional clearance and eliminate any potential intervention with the specimen. A load cell was incorporated within one end for the purpose of recording the applied load. In addition to testing back-to-back, self-drilling screwed joint configurations, the new end-connections were capable of testing conventional joint types (eg. side-butt; gusset plate) by simply being rotated 180°.

The maximum length of travel of the hydraulic ram in each direction (i.e. "opening" and "closing") was determined to be greater than the maximum displacement encountered during previous investigations (Mills & Miller 2001), thus ensuring the ram had sufficient travel prior to failure of the specimen. The hydraulic ram, the end connections and the specimen had to be as independent from the test apparatus bench as possible. This was achieved through the use of roller supports at various points positioned beneath the overall frame of the apparatus, with frictional effects considered to be minimal.

The main restraint added to the apparatus was the specimen restraint, which was implemented to prevent the specimen from lifting upward (i.e. to simulate the effect of purlins). This restraint was constructed using extended threads, which were bolted to the surface of the apparatus bench. A rectangular hollow section was then positioned above the test specimen with a clearance of approximately 5mm, whilst the height of the restraint was able to be adjusted depending on the section size being tested.

Test specimen design

Three different joint types were selected for testing, all of which were based on existing designs. Shear tests were also conducted during this phase in order to determine the nominal shear capacity of self-drilling screws to be used (i.e. size #12-14×20 & #14-10×22 screws). As a result of these tests, respective shear strengths of 2.2 kips (9.8kN) and 2.6 kips (11.8kN) were adopted.

The first joint design tested was the self-drilling screwed knee-joint, based on the successful joint prototype as described by Mills and Miller (2001). Two section sizes, namely C20015 and C25019 channel sections were used in the construction of test specimens utilising this joint type (a C20015 section is nominally 200 mm deep, 76 mm wide, 15.5 mm lip and 1.5 mm thick). Testing of the C20015 size was used to validate results obtained using the new test method compared with previous tests in Mills & Miller (2001). The C25019 size could potentially extend the concept of self-drilling screwed knee-joints to that of cyclonic conditions, given that the larger section size could carry greater loads (i.e. wind loads). Figure 2 illustrates the typical screw configurations used in the test specimens, with the only difference between the two sizes, being an additional screw positioned in each corner for the C25019 specimen in order to increase the joint capacity in line with the increased member moment capacity. Using the Proportional-Distance Method (Mills & LaBoube 2004), the theoretical knee-joint moment capacities for the proposed screw configurations and section sizes to be tested were calculated and are summarised in Table 2.

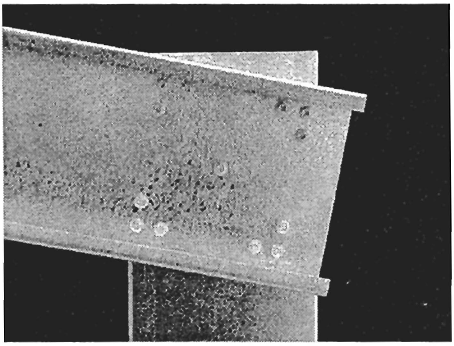

Figure 2 C20015 Self-drilling screwed knee-joint test specimen.

The second joint design tested was the side-butt knee-joint (Figure 3) for the sole purpose of determining the validity of the new test method, with the joint adopted for this investigation being the same design as that initially tested in Mills (2000). These tests confirmed once and for all the shortcomings associated with using hot-rolled steel connection techniques for cold-formed steel knee-joint designs. The joint was constructed using two C20015 sections with a 10x3x5/8 ins (255×75×16 mm) end plate welded to the end of the rafter. The rafter was fastened to the column flange with two M16 high strength bolts (5/8 ins) plus a 10x2x0.3 ins (255×50×8 mm) internal flange stiffener against the inside of the column. Two 7x1.6x0.2 ins (180×40×5 mm) web stiffeners were then welded to the column face, perpendicular to the web, in addition to the inside column flange at the joint end.

The third joint design tested was a gusset plate knee-joint (Figure 4), one of several such joint designs supplied in response to the survey. This joint type was chosen to enable a direct comparison to be made between the capacity of the self-drilling screwed knee-joint and a joint that was currently being used in cyclonic regions, the outcome of which would contribute towards determining whether or not the concept of self-drilling screwed knee-joints could be extended to cyclonic regions.

The joint was constructed using steel plate of 0.12 ins (3.0mm) thickness (Grade 300 MPa) in conjunction with C20015 channel sections and 8M16 bolts (Grade 8.8) to connect the components together.

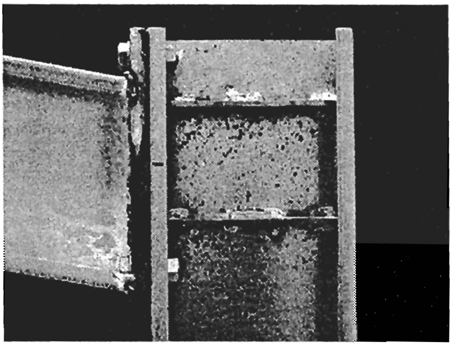

Figure 3 C20015 side-butt knee-joint

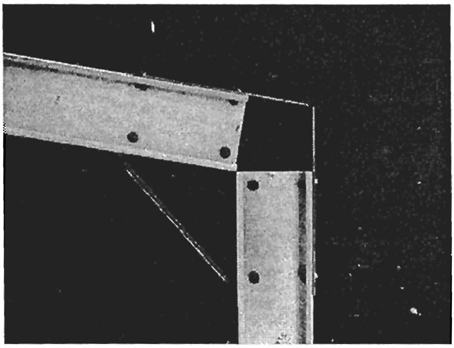

Figure 4 C20015 gusset plate knee-joint

Test results

The test program involved testing each joint type in "opening" and "closing" scenarios. One test was also conducted in opening mode using a cyclic loading to determine whether or not the cyclic effect would reduce the ultimate capacity of the joint. The description and results of each test are summarised in Tables 2 and 3.

Table 2 Summary of joint types and modes tested

Test No.	Joint Type	Test mode
Trial	Self-drilling screwed C20015 (#12-14×20)	Opening
1	Self-drilling screwed C20015 (#12-14×20)	Opening
2	Self-drilling screwed C20015 (#12-14×20)	Closing
3	C20015 Side-butt	Closing
4	C20015 Side-butt	Opening
5	Self-drilling screwed C20015 (#12-14×20)	Opening (Cyclic)
6	Self-drilling screwed C25019 (#12-14×20)	Closing
7	Self-drilling screwed C25019 (#12-14×20)	Opening
8	Self-drilling screwed C25019 (#14-10×22)	Closing
9	Self-drilling screwed C25019 (#14-10×22)	Opening
10	Gusset plate C20015	Closing
11	Gusset plate C20015	Opening

Table 3 Summary of test results.

Test No.	Theoretical Joint Capacity kip in (kNm)	Failure Moment (kNm)	Failure Mode
Trial	77 (8.7)	82 (9.3)	Member buckling
1	77 (8.7)	82 (9.3)	Member buckling
2	77 (8.7)	66 (7.5)	Member buckling
3	96 (10.9)	41 (4.6)	Member buckling
4	96 (10.9)	46 (5.2)	Member buckling
5	77 (8.7)	80 (9.0)	Member buckling
6	137 (15.5)	135 (15.3)	Screw shear
7	137 (15.5)	124 (14.0)	Screw shear
8	165 (18.6)	141 (15.9)	Member buckling
9	165 (18.6)	173 (19.6)	Member buckling
10	96 (10.9)	71 (8.0)	Plate buckling
11	96 (10.9)	88 (10.0)	Member buckling

Discussion of results

Validation of Test Method

The new test apparatus performed very reliably throughout all tests with no signs of structural weakness. The results of the Trial Test and Test 1 indicated consistency in its operation, with "opening" failure moments of 9.25 kNm and 9.28 kNm (respectively) observed for the identical test specimens (i.e. C20015 self-drilling screwed knee-joint). To further strengthen the notion of comparability, Mills and Miller (2001) recorded a similar "opening" moment of 10.14 kNm for the same type of joint tested in a universal testing machine, whilst their "closing" moment of 7.81 kNm was also akin to Test 1, which recorded 7.49 kNm. In addition, an earlier test on the same side-butt knee-joint as that tested in Test 3 produced a "closing" failure moment of 5.49 kNm (Mills 2000), as compared with 4.62 kNm for this investigation. Thus, it can be concluded that the new test apparatus provided a satisfactory and reliable method of determining failure moment capacities for knee-joint specimens, with the main advantage being a greater control over the operational environment, which led to more consistent results.

Theoretical Vs Experimental Capacities

In all cases except Tests 6 and 7 (discussed separately), the failure mode was by way of local buckling of the member, whilst the joints remained rigid. As expected, the experimental failure moments for the "closing" cases were significantly less than the corresponding "opening" cases, due to concentrated stresses acting in the compression zone of the member, as compared to the tension zone for "opening" cases.

For the self-drilling screwed knee-joints in "opening" (i.e. Tests 2, 5, 9 and Trial), the failure moments exceeded the theoretical joint capacities as predicted using the Proportional-Distance Method, suggesting that this method of joint design is conservative for opening moments. Conversely, the experimental failure moments for joints in "closing" (i.e. Tests 1 and 8) were less than the theoretical joint capacities, although ultimate failure of the test specimens still occurred via member buckling (i.e. prior to joint failure), indicating that the joint capacities were yet to be reached. This result implies that the Proportional-Distance Method can still be relied upon as a useful means of determining the theoretical joint capacity, particularly given that the upward loading case is the critical design scenario in Australia.

Tests 6 & 7 involved the construction of C25019 self-drilling screwed knee-joints using Size #12 screws, which proved to be inadequate for the larger section size. When tested, the failure mode for both the "opening" and "closing" cases was by way of screw shear, which effectively provided the most accurate means of confirming the reliability of the method for calculating the theoretical joint capacity. For the "opening" case, the failure moment of 14.0 kNm was less than the theoretical joint capacity of 15.5 kNm, indicating that the application of a capacity reduction factor of 0.9 to the theoretical joint design capacity would be acceptable, whilst in "closing", the failure moment was closer to theoretical at 15.3 kNm.

The results for the side-butt knee-joint were not unexpected with the failure moments for both the "opening" and "closing" cases being considerably less than the theoretical joint capacity, confirming once and for all the inadequacy of using hot-rolled joint designs with cold-formed steel. As previously stated, this joint type was included in the project primarily for comparative purposes in order to validate the test method.

The gusset plate knee-joints also produced failure moments in both the "opening" and "closing" cases that were less than predicted, however, unlike the side-butt joint, these were more in line with the member section capacity. Given the complexities involved with calculating the theoretical capacity of a three dimensional joint from first principles, computer modelling for this purpose is therefore recommended in future.

Comparison of Knee-joint Types

Of the joints tested, the gusset plate and self-drilling screwed knee-joints were shown to be the strongest joint designs, based on a uniform section size of C20015, whilst the performance of the side-butt joint again proved to be unsatisfactory. More significantly, however, the tests demonstrated that the self-drilling screwed joint was comparable in strength to an actual joint design currently being used in cyclonic regions, although the gusset plate joint proved to be marginally superior.

The results for the C25019 self-drilling screwed knee-joint (size #14 screws) were also encouraging (i.e. significantly greater than the C20015 joint), although time and budgetary restraints prevented a comparative test with a gusset plate specimen from being undertaken.

Self-drilling Screwed Knee-joints in Cyclonic Regions

Table 3 outlines the limitations of the C20015 and C25019 self-drilling screwed knee-joints with respect to wind region and terrain category. These scenarios have been determined by comparing the design bending moments (M^*), as produced by the critical wind loading cases for a typical sized portal-framed shed, with the experimental joint failure moments (M) obtained during testing.

Table 4 Limiting bending moments for self-drilling screwed knee-joints

Wind Region / Terrain Category	Section Size	Joint Action	Moment Comparison
A3	C20015	Opening	$M^* = 8.14 < M = 9.0$ kNm
		Closing	$M^* = 3.51 < M = 7.5$ kNm
C3	C25019	Opening	$M^* = 16.7 < M = 19.6$ kNm
		Closing	$M^* = 6.44 < M = 15.9$ kNm

Whilst the C20015 self-drilling screwed knee-joint was shown to be comparable with a joint type that is currently used in cyclonic regions, it can be seen from the above analysis that in this instance the joint size would in fact be limited to non-cyclonic loading conditions. On the other hand, the C25019 joint (size #14 screws) would be capable of withstanding wind loadings relevant to Region C3 conditions (i.e. cyclonic) based on the selected shed size. Region D3 critical cases were also considered, however these produced significantly greater design moments (up to 27.4 kNm), which could not be achieved using the joint sizes considered. Given the additional number of screws that would be required to increase the joint capacity to accommodate these loading conditions, it may not be practical to construct a shed of this nature using larger sized sections (eg. C30024).

Conclusions & recommendations

The development of a successful test apparatus was an essential part of the investigation, with the outcome in turn being responsible for determining the overall success of the project. The method of testing was particularly versatile as it enabled a variety of joint types to be tested and compared due to similar loading characteristics being applied through the specimen members during all tests. The new test apparatus was considered to be both reliable and consistent in its performance, thus suggesting that its capabilities could be extended to commercial applications. In addition, a parametric study examining the relationship between the section size and respective joint failure moments could also be conducted.

From the test results that followed, it can be concluded that the self-drilling screwed knee-joint is capable of withstanding loads that are comparable to those experienced in cyclonic conditions. However, the cyclic loading test was deemed to be inconclusive in determining whether its performance could be sustained under these conditions. Although the joint remained unhindered and the self-drilling screws appeared to retain fixity between the members, the number of cycles was limited by comparison to realistic wind conditions. However, self-drilling screws are already recommended as roof fixing screws in cyclonic regions so it is not anticipated that cyclic loading will be a problem for such joints.

When comparing the overall performance of the self-drilling screwed knee-joint to a joint design that is currently being used in cyclonic regions (i.e. the gusset plate), the considerable cost difference should also be considered. The material cost of the gusset plate (and bolts) was calculated to be approximately ten times the cost of the self-drilling screws, notwithstanding the cost of fabrication, thereby suggesting the self-drilling screwed joint to be an economical alternative as well.

The major conclusion to arise from this study is that several joint types, including self-drilling screwed joints may be suitable for knee-joints in cyclonic regions, but that the traditional side butt joint should not be used. An economical and reliable testing method such as that developed in this study should be used by shed manufacturers to ensure that their knee-joint designs are adequate, particularly if the joint design has been based on a hot-rolled steel joint model.

Acknowledgements

The authors would like to thank Bluescope Steel (Lysaght) for providing materials for testing.

Appendix. - References

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