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Research Article

Finite Element Models for Thin-Walled Steel Member Connections

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The behavior of connections associated with the thin-walled steel members is distinctly different from that of hot-rolled steel connections, primarily because of the flexibility of the plates. A typical cold-formed steel structural construction may entail such numerous connections. The incorporation of large number of such connections in an analysis and design, using sophisticated finite element models, is very tedious and time consuming and may present computational difficulties. The objective of this investigation is to create simplified, yet reasonably accurate, finite element models for the analysis of screw connections and bolted connections associated with thin-walled sheet steel construction. The primary plates were modeled using quadrilateral shell elements, and nonlinear stress-strain relationship was established based on experiments. The fasteners were modeled as an elastic medium. The plate-to-plate interactions and the plate-to-screw interactions were incorporated using contact elements. The study considered two finite element models of different complexity. The performance of these models was established through comparisons with the corresponding experimental results. The finite element analysis results exhibit reasonably good agreement with the test results in terms of connection stiffness, screw tilting, end curling, and average longitudinal strain. The recommended simplified connection model is capable of reproducing the behavior of sheet steel screw and bolt connections.

1. Introduction

Welding and mechanical fastening are the two most common types of connections in steel construction. Though thin-walled steel members, such as cold-formed steel structural members, may be welded together, mechanical connections are convenient and economical and, thus, are widely used in light-weight steel construction. The mechanical fasteners may be screws, bolts and nuts, blind rivets, short pins, and so forth. Figure 1 shows a sample of thin-walled sheet steel lap connection that is under consideration in this paper. The behavior of screw connections and bolt connections associated with the thin-walled steel members is distinctly atypical primarily because of the flexibility of the plates. Tilting of fasteners in the hole, pullover of the screws, distortion of the sheet metal around the hole in tension, and so forth contribute to this distinction as well. Previous studies [1–5] on such screw connections and bolted connections experiencing various failure modes were experimental investigations as well as finite-element-based numerical analytical investigations. The analytical studies concentrated on the stress and strain states in the vicinity of the screws or bolts, screw/bolt-plate interaction, friction between plates, effect of grips of bolts, effect of bolt tightening on the connection, corresponding ultimate strength of such connections, and so forth. Consequently, the finite element models used in these studies [2, 5] focused on detailed modeling of the connection region. Though such models may be effective for understanding the comprehensive behavior of a connection, they may be of limited interest to structural engineers, who frequently encounter structures with large number of connections in which the strength of the structure is dictated by the member strength rather than the connection failure. Few examples of such type of noncritical connections are screw fastened web stiffeners, screw fastened reinforcements, screw fastened sheet metal flooring, and so forth. In such connections the stiffness of the connection plays an important role on the overall behavior

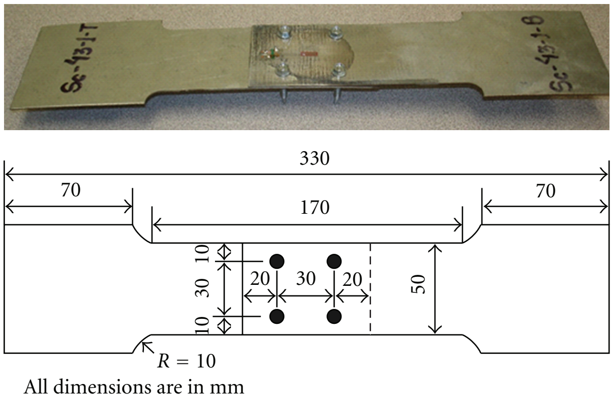


Figure 1: Thin-walled sheet steel lap connection.

of the structure rather than the strength of the connections themselves. Besides, detail modeling of large number of such connections is not only very tedious and time consuming but also may cause numerical convergence difficulties. Therefore, it is desirable to develop a simplified finite element model of a connection which accurately captures the connection behavior in the elastic range, without much regard to joint failure modes or stress/strain state in the vicinity of the screws or bolts. This paper discusses the development of simplified finite element models for thin-walled sheet steel connections using self-drilling screws and bolts, which are validated through comparison with experimental results.

2. Self-Drilling Screw Connections

Self-drilling screws are externally threaded fasteners with the ability to drill their own hole and form their own internal threads. Self-drilling screws are either carbon steel plated with zinc for corrosion protection or stainless steel with carbon steel drill point and plated with zinc for lubrication. The use of self-drilling screws has become popular in thin-walled sheet steel construction because of their inherent advantages such that, it drills hole itself, forms mating thread, and clamps the two or more thin steel sheets in one easy operation. The self-drilling ensures correct hole size every time, resulting in better thread engagement and tighter clamp. The fastening process does not need power drills and drill bits, and it does not require elaborate and costly press tools, machine taps, and their maintenance. Only tool required is a simple screw driver. In summary, self-drilling screws can provide a rapid, effective, and economical means to fasten thin-walled steel members such as cold-formed steel structural members.

2.1. Failure Modes in Screw Connections. The failure modes associated with the screw connections in thin-walled steel members can be categorized into two types: connecting plate (main member) failure and screw failure. Main member plate failure includes rupture of the net section, bearing failure of the plate, and pullover of the plate. The net section failure is characterized by the fracture of the connected plate across the screw holes perpendicular to the loading direction. The current North American Specification for the Design of Cold-Formed Steel Structural Members [6] stipulates the corresponding nominal load capacity P_n as $P_n = A_{\text{net}} F_u$, where A_{net} is the critical effective net cross-sectional area and F_u is tensile strength of the connected part. The bearing failure is essentially piling up of steel sheet behind the screws. Studies indicate that the bearing strength of the connected plate depends on several parameters, including thickness of plates, tensile strength of the connected plates, and F_u/F_y ratio of the connected part. The corresponding provision [6] for strength, without consideration of hole deformation, is given as $P_n = C m_f d t F_u$, where C is a bearing factor which depends on the thickness of the connected parts and on the ratio of fastener diameter to member thickness, m_f is modification factor for the type of bearing connection, d is the nominal diameter of the screw, t is the thickness of the connected plate, and F_u is tensile strength of the sheet. The pull-over mode of failure may occur in thin-walled metal connections, where the thin plate wraps itself around the head of the screw and tears and pulls over the screw head. The pull-over provision according to AISI Standard [6] is $P_n = 1.5 t_1 d'_w F_{u1}$, where t_1 is the thickness of the connected plate in contact with the screw head, d'_w is the larger of screw head diameter and washer diameter, and F_{u1} is the tensile strength of the plate in contact with screw head. Flat washers under the screw head are often used to prevent the pull-over failure.

Screw failure consists of shear failure of screws, pull-out failure, and excessive screw tilting. Screw lap connection transfers the load from one plate to another plate by means of shear. The nominal shear strength of the screw is often taken as P_{ss}, which is the shear strength of screw as reported by manufacturer or determined by independent laboratory testing. Screws pulled out from the thin plate base one termed as pull-out mode of failure. The often stated reasons for pull-out failure are inadequate stiffness of connected thin plate to grab the screw thread around the opening, shearing of screw threads thus pull-out, and elongation of screw and eventual breaking in tension. The nominal pull-out strength of a screw is given by AISI [6] as $P_{\text{not}} = 0.85 t_c d F_{u2}$, where t_c is the lesser of depth of penetration and thickness of the member not in contact with screw head or washer, d is the nominal screw diameter, and F_{u2} is the tensile strength of the plate not in contact with screw head. Because of inherent eccentricity associated with the lap connection, the screw is always subjected to tilting action. For thick plate connections, the screw tilting is controlled by yield strength of the connected plate. However, for thin plate connections, screw tilting is influenced by the bending stiffness around the openings (plate thickness). Tilting of the plate often leads to screw pull-out and pull-over failures. The corresponding strengths are specified in AISI [6], however, in the interest of brevity, are not given herein.

3. Experimental Behavior of Thin-Walled Steel Lap Connections

Experimental part of this research established results that may be used to validate the finite element models of screw and bolt connections. The connection type under consideration is a lap connection with four screws (or bolts) arranged in a square pattern as shown in Figure 1. The connection was designed in such a way that it would fail at the net section. In other words, the tensile strength of the net section across the width along the screw line was less than the pull-over strength, pull-out strength of screw and the shear strength of the screw. The width and the length of the overlapped portion of the connection were selected to satisfy the AISI [6] connection requirements. Accordingly, the minimum overlap length and the width of the connection are governed by the size of the screws, spacing of the screws (shall not be less than 3 times the diameter of the screw), and edge and end distances (shall not be less than 1.5 times the diameter of the screws). As evident from Figure 1, the ends of the test specimen were made wider than the width of the connection, and smooth curve transition zones were provided between the end part and the actual connection part to minimize the stress concentration. Wider ends and smooth transitions ensure failure at the connection. The specimens were cut from the web of a randomly selected cold-formed steel section. The specimens were cut along the longitudinal direction of the steel section, which is parallel to the direction of rolling for such steel sections. The coupons were then machined to shape and dimensions as shown in Figure 1. Three lap connection specimens were fabricated using number 8 self-drilling screws, and other three test specimens were connected using 5 mm diameter high strength steel bolts. The base metal thickness was measured after removing the galvanized layer on the metal surface. The galvanized surface was removed by dipping one end of tensile coupons into the hydrochloric acid. The average base metal thickness of the connecting plates was measured to be 1.11 mm.

Figure 2 shows overall test setup used in this experimental investigation. The test load was applied to the specimen using the 30 kN loading range of a 600 kN capacity Tinious Olsen loading machine. The test specimens were mounted in the testing machine using gripping devices and aligned with respect to the vertical axis of the machine. An extensometer was mounted on the specimen to measure the gauge extension. A string pot was placed to measure relative displacement of the tip of the screws. The relative displacement of the tip of the screw allows us to determine the tilting of the screw relative to its initial orientation. The grip extension of the machine was also monitored. A 5 mm electric resistance strain gauge was used to measure the strain at the connection zone. Strain gauges had a capacity to measure 3% strain with 0.5% accuracy. Once the test specimen was placed in position and instrumentation is completed, the initial readings for the load cell, displacement transducers, and strain gauges were set to zero. Although no test protocol for the loading rate for such type of testing was found, the loading rate was controlled such that (a) sufficient load-displacement points can be recorded for graphing (60 readings per kN tensile load) and (b) average stress rate of the section does not exceed the stress rate specified by ASTM for tensile coupon test (690 MPa/min). The readings from the machine (load readings), string pots, and the strain gauges were recorded using a data acquisition system and a personal computer. The loading was continued until the connection failure. In the next section, the experimental results are presented along with the finite element simulation results.

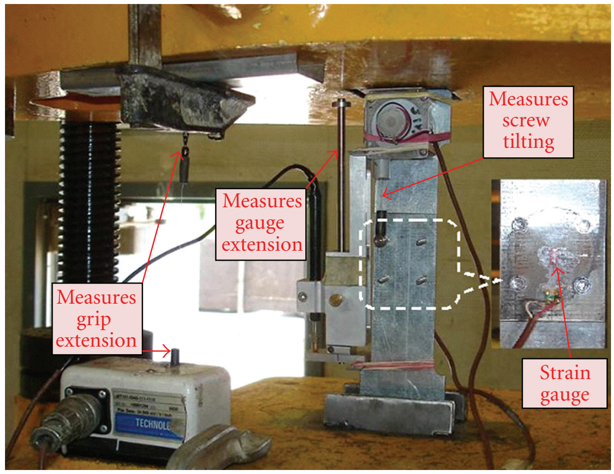


FIGURE 2: The test setup.

4. Finite Element Models for Connections

4.1. Modeling Considerations. In order to develop an appropriate finite element model, first of all, it is necessary to identify all possible physical actions involved within the structural system under consideration. The following actions are dominant in a lap screwed or a lap bolted connection. *Shear transformation:* the main function of a structural connection is to transfer a load from one structural part to another structural part. Depending on the type of connection and types of applied load, the connecting elements such as screws, bolts, rivets, welds, and so forth, may be subjected to compression, tension, shear, torsion, and bending. In lap connections the load is transferred into another plate primarily by means of shear transfer through the screws. *Screw-to-plate contact:* load from the plate to the screws is primarily transferred through a direct contact action. Thus, a 3D no penetration contact surface element may be used to incorporate such contact actions between the plate and the screw. *Plate-to-plate contact:* in a lap joint, two plates are fastened together though the plates exist in two parallel planes. When the lap joint is subjected to tensile loading, however, these two parallel planes would attempt to align themselves into a single plane. In such a process, the two plates would begin to come into contact with each other. Again, 3-D no penetration contact surface elements may be used to handle such contact action between the main connecting plates. *Screw tilting:* eccentricity of the lap connection would cause tilting of screws. Screw tilting decreases the overall stiffness of the connection. *Curling:* the out-of-plane deformation of the free end of the connection is known as curling. Effects of curling on the ultimate strength of connection had been discussed in various studies [7, 8]. Chong and Matlock [7] and Winter [8] experimentally demonstrated considerable curling or bending of ends out of original plane in thin-walled steel connections; however, the suggested that the load carrying capacity of such connections may not be significantly affected by such a curling. However, Kim and Kuwamura [5] showed that the reduction of ultimate strength of curled specimen may be from 4% to 25% compared with the specimen restrained against curling and concluded that curling has a considerable effect on the ultimate strength of connections and should be considered in estimating the ultimate strength. Effect of curling in the connection stiffness was also incorporated in this study. Some of the other important factors to be considered in finite element modeling are boundary conditions, load paths, and large displacement of any structural part because of buckling/bending/rotation.

The test specimens under study were taken from cold-formed steel sections, and the mechanical properties of cold-formed steel sections are considerably different from that of the virgin sheet steel, particularly at the corners of cold-formed structural shapes. This difference primarily arises due to the manufacturing process, such as cold-roll forming, cold bending, and so forth. Studies by Abdel-Rahman and Sivakumaran [9] showed that the material properties on the flat regions are similar to the properties of virgin steel. Three tension coupon tests of flat portion of the web of the cold-formed section were used to derive an idealized stress-strain relation for the finite element model. Experimental and idealized stress-strain relations used for the thin-walled sheet steel connections under consideration are shown in Figure 3. Since the sheet steel material is ductile, von-Mises failure criterion was applied, which states that failure occurs when the energy of distortion reaches the same energy for yield in uniaxial tension. It is assumed that the sheet steel is weaker than the screws and thus the connecting sheets would fail prior to screw failure. Since the screws are usually made from the higher-strength steel, screws were assumed to be an elastic material, with modulus of elasticity of 203 GPa and a Poisons' ratio of 0.3.

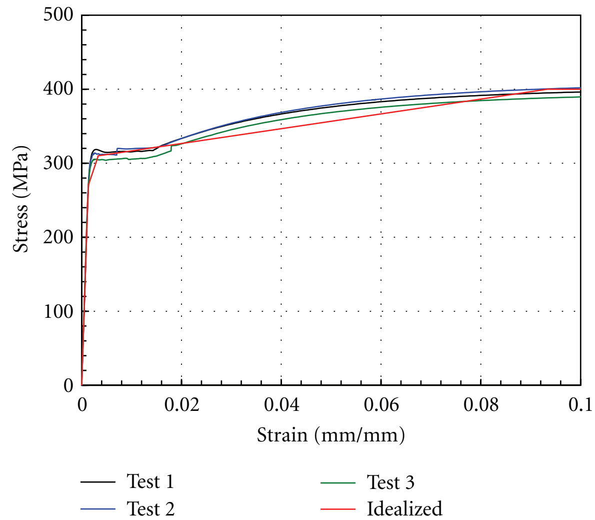


FIGURE 3: Experimental and idealized stress strain relationship for thin-walled steel.

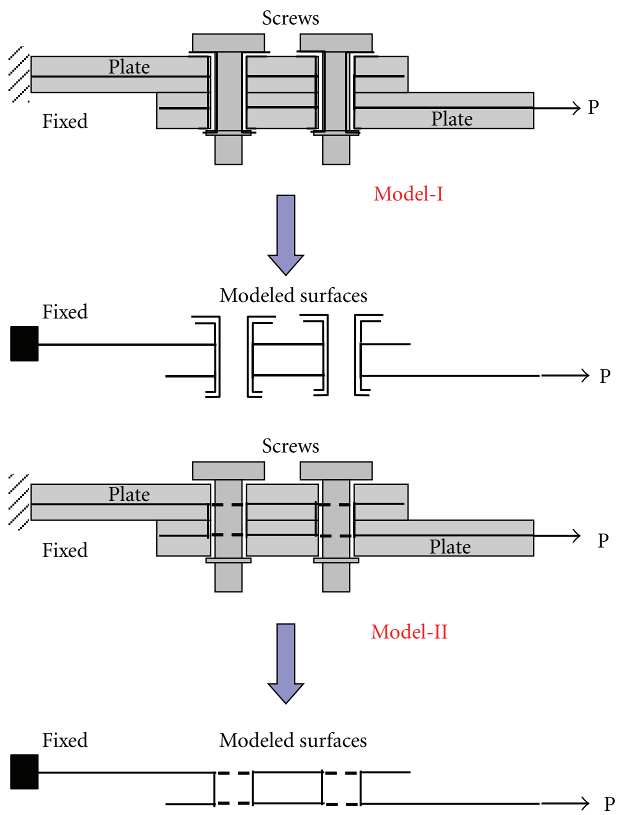


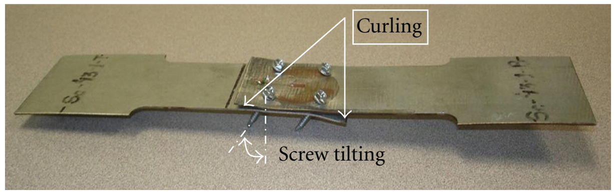
FIGURE 4: The connection models.

4.2. The Connection Models. The finite element models for the thin-walled sheet steel connections were developed using the commercial multipurpose nonlinear finite element program ADINA [10]. Two connection models were built for this investigation and are shown in Figure 4. These models are herein identified as Model I and Model II. Thin-walled sheet steel connections are susceptible for high localized deformations. To incorporate such large local displacements and rotation of screws, a geometrically and materially nonlinear finite element formulation was used. Four-noded shell element was used to model the surfaces of connecting plates and the screw. A gap between two connecting plates within the overlap region was set as equal to the thickness of plate. Such a gap is essential to represent the eccentricity of loading in the lap connections. Contact surfaces are defined as surfaces that are initially in contact or are anticipated to come into contact during the response solution. Plate-to-plate or plate-to-screw contacts can be expected in thin-walled sheet steel connections. Three-dimensional contact elements are available in ADINA [10] element library to define contacts between two surfaces. The corresponding contact surfaces are defined as contact pairs. One of the contact surfaces in the pair is designated as the contactor surface, and the other contact surface is designated as the target surface. Action of contact occurs when the plane or line defined by the contact segment nodes of target surface is penetrated by the nodes of contractor surfaces. The contact elements used in this study are capable of taking into account repeated contact and separation actions.

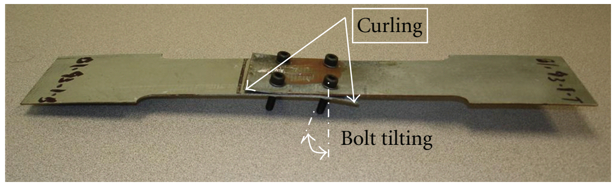
The Model I uses 3D no penetration contact surface elements in order to capture the plate-to-screw contacts and plate-to-plate contacts. In this model, the force from plate to the screw is transferred through the contact elements. Contact elements have been used between the connecting plates in order to capture the plate-to-plate interaction. Furthermore, contact surfaces were also defined between plate edge around the hole and the top and bottom ends of the screw. Such a connection model is capable of capturing the complete pull-over physical interactions between the plates and the screws. Model I represents a more realistic connection. However, this model involves somewhat cumbersome modeling. It would be tedious and time consuming to use such a model if the structural problem involves a large number of such connections.

Model II incorporates only the plate-to-plate contact phenomenon. In this model, the screws were assumed to be continuously connected to the plates. Therefore there is no contact action between screws and plates. In Model II, only the outer surfaces of screws were modeled, using shell elements, as a hollow shaft between two plates. Same nodes were assigned to the screws and plates around the edge of plate holes. Possible contact actions between the plates were incorporated using “single-sided contact surface” elements. Friction between two plates was assumed to be zero. This model is far simpler than the Model I. Such a connection model can be built very fast. Both connection models were used to investigate the behavior of 70 mm lap joint.

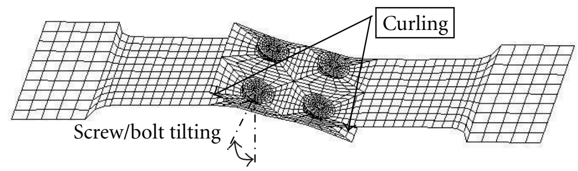
The most frequently used iteration scheme for the solution of nonlinear finite element equations, Newton-Raphson iteration scheme, was used in this investigation. An energy convergence criterion was applied to solve the equilibrium equations. The quality of mesh was checked in terms of aspect ratio, war page, and skew of the elements. Ratio of the longest edge to shortest edge was maintained less than 5, and ratio of shortest edge to thickness also maintained to be 5. Warpage (the amount by which an element deviates from being planer) was kept less than 15°. Similarly, the skew of the element was less than 60°. The screw connection problem in thin-walled structures such as cold-formed steel is small strain and large deformation problem. The total Lagrangian formulation can be used for small strain and large deformation problem [11]. The total Lagragian formulation includes all kinematic nonlinear effects due to large displacements and rotations, but small strains. In this investigation displacement control analysis was used which enforces prescribed displacement at the selected points. One end of the connection assembly was fixed against all translations and rotations. Other end was subjected to uniform translation along the width of the connection.



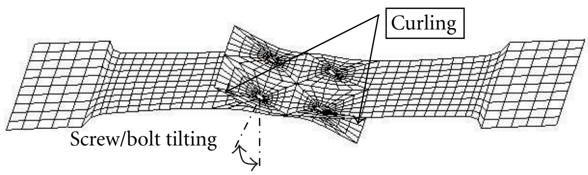
(a) Screw connection—Experiment



(b) Bolted connection—Experiment



(c) Screw/Bolted Connection—MODEL-I



(d) Screw/Bolted Connection—MODEL-II

Figure 5: Comparison of experimental failure modes and analytical failure modes (a) screw connection, (b) bolted connection, and (c) Model I, and (d) Model II.

5. Results and Discussions

Here, the finite element analysis results are compared with the experimental results. Figure 5 shows a typical screw connected specimen and a bolt connected specimen after testing, as well as the deformed shapes of finite element models at peak loads. Note that the finite element models do not distinguish between screw connection and bolt connection; however, two different models, namely Model I and Model II, are under consideration. In the experiments the final failure of the specimen was triggered by the net section yielding. Both, finite element and experimental result show evidence of end curling which have been identified in Figure 5. In terms of qualitative deformed shapes, both the experimental results and the finite element model results show good agreement. Figures 6 and 7 show the quantitative experimental results and the finite element results for screw connections. Measurements were taken during the experiments in order to quantify the gauge extension, screw tilting, average strains, and end curling for both screw and bolt connections. However, in the interest of brevity, only sample plots are presented here. Figure 6 focuses on the gauge extension of screw connections. Three identical test specimens, recognizing the variability associated with the screw-fastening mechanism, exhibited reasonably consistent load extension relations. Both finite element models, Model I and Model II, give load-gauge extension results that are in

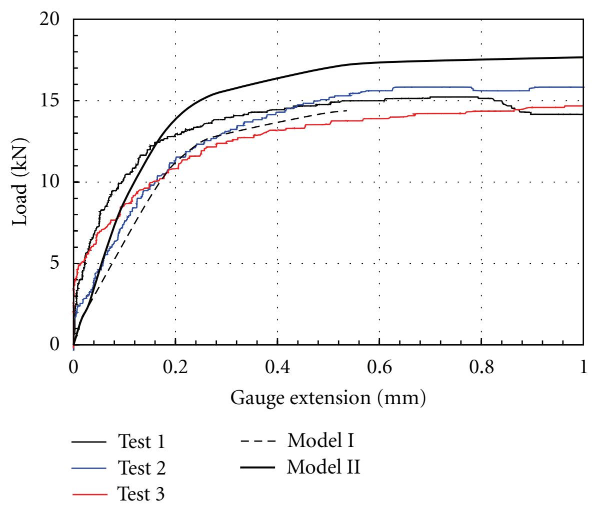


Figure 6: Gauge extension of the screw connection.

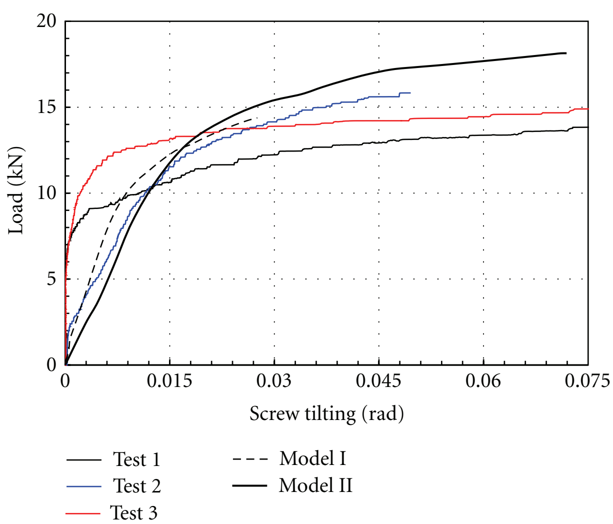


Figure 7: Screw tilting of the screw connection.

reasonably good agreement with these experimental results. It is evident that the Model II predicted stiffness fits well with the experimental results. On the other hand, Model I, though it is computationally demanding, appears to better predict the ultimate strength of connection. Figure 7 shows the screw tilting measurements in screw connections. In the beginning of the experiment, screw tilting was not noticeable in two out of three experiments; however, the finite element results show a linear screw tilting behavior right from the very beginning. However, both models were capable of capturing the screw tilting at higher load levels.

Similar comparisons were made for the bolted connections, which are not shown here. Based on experimental results, it was noted that, in general, the bolted connections are flexible than the self-tapping screw connections. Consequently, the Model I stiffness values fit well with the bolted connection load-gauge extension results, and Model II exhibited a stiffer connection behavior than the bolted connection experimental results. Both finite element connection models seem capable of capturing bolt tilting.

Compatible strains and curling of test specimens were observed for both screw connections and bolted connections. As a side investigation, the impact of curling in the connection behavior was explored. Model II was used to investigate the effect of curling on the connection stiffness of a screw connection. Curling was prevented by restricting the out-of-plane displacements along the connected edge of the plate. The result shows that preventing curling makes the connection stiffer by as much as 5%. Moreover, the prevention of curling reduces the screw tilting by up to 33%.

6. Conclusions

The behavior of screw connections associated with the thin-walled sheet steel members, like cold-formed steel members, is characterized by the low plate stiffness values. Most of the previous studies on connections focused on the behavior and the ultimate strength of the thick plate connections. Some of the studies on thin sheet steel connections concentrated on the stress and strain states in the vicinity of screws or bolts, which often involved cumbersome modeling of the connection regions. Structural systems frequently encounter large number of connections, where the connections rarely fail; however, they significantly contribute to the structural stiffness. Incorporating large number of connections using sophisticated finite element models is not only very tedious and time consuming but also may present numerical and computational difficulties. In this study two simplified finite element models were developed for screw fastened thin-walled steel connections. The main members (connecting plates) were modeled using quadrilateral shell elements utilizing nonlinear stress-strain relationship based on experiments. A von Mises criterion was applied for yielding. Large displacement/small strain formulation was used for such analysis. Two types of finite element models, utilizing contact elements, were under consideration; Model I captures the plate-to-plate interactions and the plate-to-screw interactions, including the pull-over mode, whereas the Model II focuses on the plate-to-plate interactions only. The performance of these finite element models was evaluated against experimental results from three identical specimens each of screw fastened connections and bolt fastened connections. It was observed that, in general, the finite element analysis results were in a good agreement with experimental results in terms of connection stiffness, screw tilting, end curling, and average longitudinal strain. However, on balance, Model II, which incorporates the plate-to-plate interactions only, might adequately capture the influence of screw connections on the behavior and strength of thin-walled steel members having such connection. In essence, the simple finite element connection proposed here as Model II is capable of replicating the behavior of such connections in thin-walled steel members.

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