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Design of steel transmission pole base plates using yield line method

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ABSTRACT

Steel transmission poles are widely used for their strength, ease of construction, small footprint, and aesthetic appearance. These poles can be either directly embedded into their foundations or supported on based plates which are connected to the reinforced concrete footings via group of anchor bolts.

There are few available published methods for the analysis and design of this type of base plate connection. These methods are not widely used in the industry as they are either complex, lack solid theoretical background, or yield results that are not consistent with manufacturer's time-tested proprietary design methods. Therefore, there is a need for an accurate method suitable for technical or design office for designing these connections when subjected to axial loads, bending moments or the combined effect of both.

This paper presents a numerical study performed on the base plates of polygonal steel poles that are supported directly on anchor bolts with levelling nuts and subjected to bending moment and axial load. The Finite Element (FE) analysis part of the work is carried out using ADINA software and the results obtained from the analyses are compared with published experimental results from which it is concluded that the finite element model can accurately predict the behaviour of these connections.

Parametric investigation is then conducted to gain more insight into the behaviour of these base plate connections and to use the obtained data the validation of the proposed design method. The parametric investigation covered the behaviour of these connections under pure axial load and pure bending moment while the varying parameters considered included number of shaft sides, base plate thickness, number of anchor bolts and anchor bolt diameter.

Design formulae based on the yield line theory are then proposed and a comparison between the yield loads calculated using the proposed expressions and finite element results is presented. The yield loads resulting from using the proposed design method agreed with the finite element results with a maximum calculated difference of 13%.

1. Introduction

Steel transmission poles are used for the advantages they bring to transmission lines that include speed of assembly and erection, ease of construction, appearance, and limited footprint. There are several methods for connecting these structures to their foundations one of which is through base plates and anchor bolts embedded in their reinforced concrete footing. Transmission poles with base plate on anchor bolts connections are designed through either implementing steel pole manufacturers proprietary design methods, following the methodology presented in ASCE 48, Design of Steel Transmission Pole Structures standard [1], or rarely using finite element analysis.

Steel transmission pole base plate connections are typically detailed as ring plate that is joined to the steel shaft using full penetration weld with an additional outer reinforcement fillet weld. Anchor bolts connecting these base plates to concrete footings can be equally spaced arranged in circular pattern or placed in clusters considering the predominant bending moment directions. The design of these connections is then achieved by proportioning the plate and anchor bolts to resist the acting shear force, axial force and bending moment.

Connection design in general has been studied extensively and design guidelines are available in design standards and published literature [21,24]. However, this is not the case with circular base plates supported directly on anchor bolt, although their use is common, as published literature has come short of recommending an accurate and simplified design method for their design.

ASCE 48 includes, in an appendix, a simplified design method developed for eight-sided and twelve-sided shafts using effective bend-

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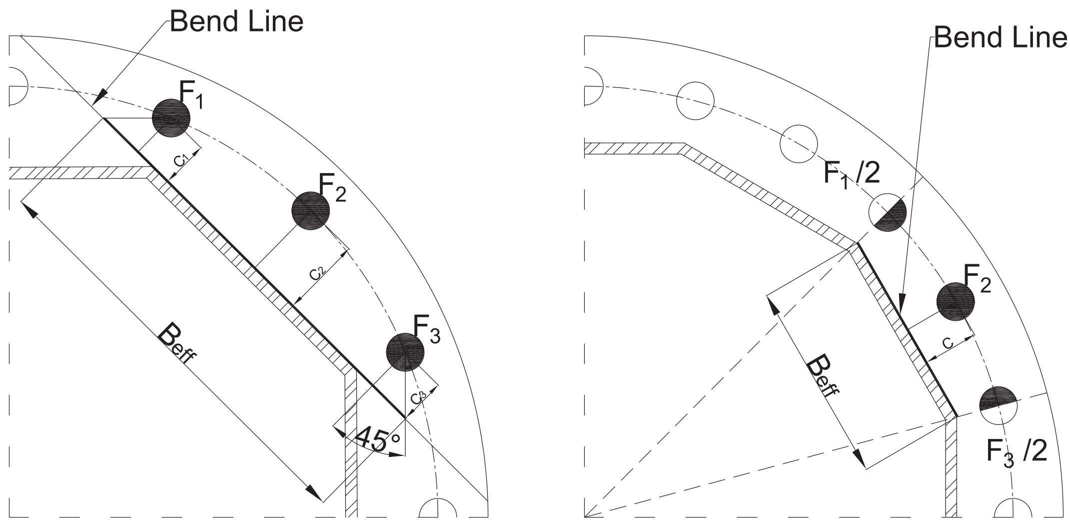


Fig. 1. ASCE – 48 Bend Line and Modified Bend Line Methods.

line lengths based on defining critical sections parallel to the pole flats and limited in width by a 45-degree lines radiating from the centre of the two outermost anchors as shown in the Fig. 1. Force in each anchor bolt is calculated based on the acting bending moment and axial force on the group of anchor bolts. The bending moment in the base plate produced by the force in each of the anchor bolts included in this critical section is then calculated at the face of the shaft. The adequacy of the cross section, rectangular in shape with the plate thickness as the single design variable, is then checked under the effect of the acting bending moment. This method was modified in the 2019 edition of the ASCE-48 standard where few changes are introduced that included: limiting the effective bend lines lengths to that of each shaft face; bolts that act on each face are those that fall within a wedge created by extending the vertexes from the centre of the shaft radially; and bolt holes that fall on a vertex act half on one face and half on the other face. A comparison between the designed base plate thicknesses using this method and those produced by steel pole manufacturers is also included in the appendix. Base plate thicknesses calculated using this method showed a close correlation with the data submitted from the fabricators participated in that study.

There are few published studies that examined the behaviour of circular flange plate connections under the effect of pure bending or the combined effect of axial load and bending moment. In their paper [2,3], studied the bending behaviour of flange plate connections under pure bending. The main objective of the study was to recommend a practical design model for these connections. In the experimental part of their study four types of bolted flange plate connections were tested. The study then proceeded with finite element modelling of the connections and used the experimental test results for verifying the accuracy of the results obtained from the models. The study was then extended to calculate the bending capacity of these connections using the principle of virtual work. In another study [4], presented an analytical model for the calculation of the static resistance of bolted circular flange connections subjected to a combined bending moment and axial force considering the influence of the joint ductility. An analytical model was presented to evaluate the stiffness of the tensile and the compressive parts of the connection from which the connection initial rotational stiffness is calculated. The proposed method produced results that compared well with available experimental as well as finite element simulation results. The previous two studies, as well as other available studies in the literature, considered the flange plate to be in full contact with the other flange in the connection and not supported directly by bolts. This main difference does change the behaviour of the connection thus the findings cannot be applied to the design of base plate supported on anchor bolts.

Recognizing the difference between the behaviour of circular base plates on anchor bolts and those with full contact surface [5], executed a research program to study the behaviour of the former configuration when subjected to bending moment. In that study, three variables were considered: plate thickness, anchor bolt diameter, and the presence of stiffeners. A test program was then devised where a total of twelve specimens were loaded in bending to failure. This was followed by suggesting a design formula for the design of the base plate connection based on yield line approach. Although this formula yielded acceptable results it was complicated which rendered it not suitable for hand or spreadsheet calculations. In a subsequent numerical and analytical study, Khedr and Heikal [6] conducted a parametric study using finite element method that was followed by presenting a simplified yield line design method for base plate on anchor bolts connection subjected to bending moment. The yield line formula deduced in their study was only calibrated for pipes with circular cross sections resting on eight anchor bolts.

The current study aims at gaining a better understanding of the behaviour of pole base plates supported directly on anchor bolts under the effects of axial load or bending moment and to present simple method for the design of these connections based on yield line theory for the two load cases. Three-dimensional finite element model of the shaft, base plate, and anchor bolts is first developed considering material nonlinearities and contact between anchor bolts and base plate. The assumptions used in the development of the model, see Section 2, are then verified using published test results. Parametric investigation is then performed using FE analysis to evaluate the effect changing the design parameters have on the behaviour of the connection and to provide data set for the validation of the analytical part of the work. Simple formulae for the design of the base plates based on the yield line theory are presented followed by a discussion on the suitability of their use in designing base plates with different configurations.

2. Finite element model

2.1. General

The behaviour of the base plate connection under investigation is studied by constructing a series of three-dimensional (3D) finite element models using the finite element software ADINA [20] considering various geometries covering the range of the design variable considered. The FE models utilize multilinear elastic-plastic material models for the different steel components of the connection, bolt elements with pretension load, and contact elements to simulate separation between

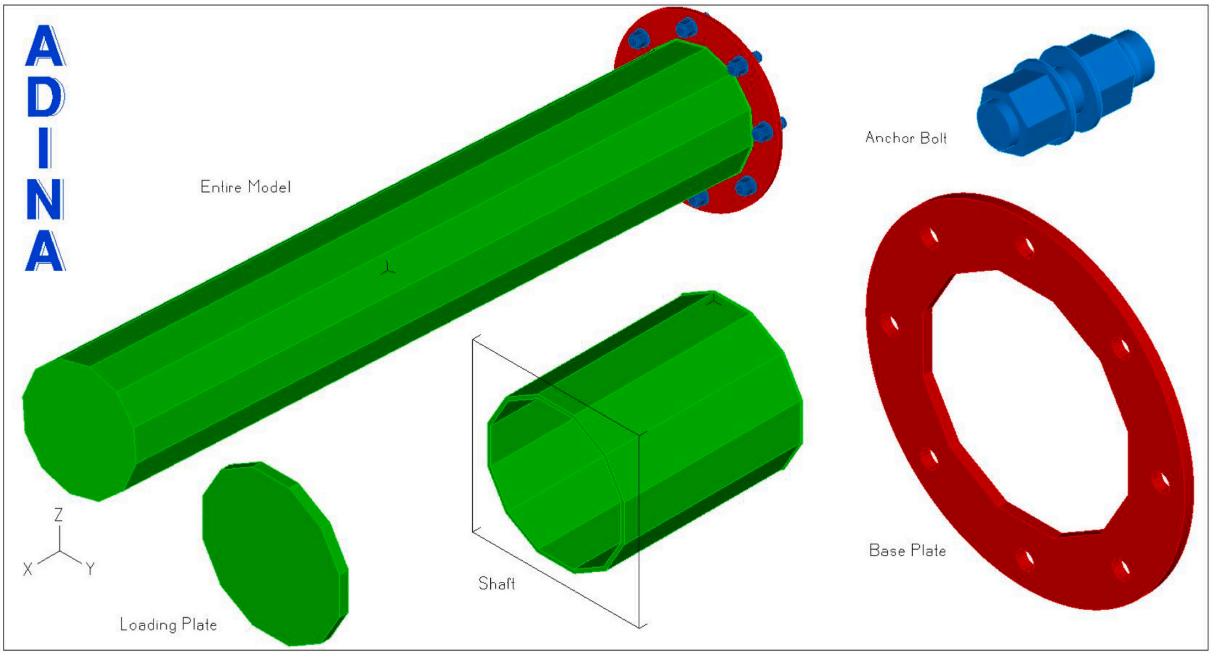


Fig. 2. Three Dimension View of the Finite Element Model Used in the Study.

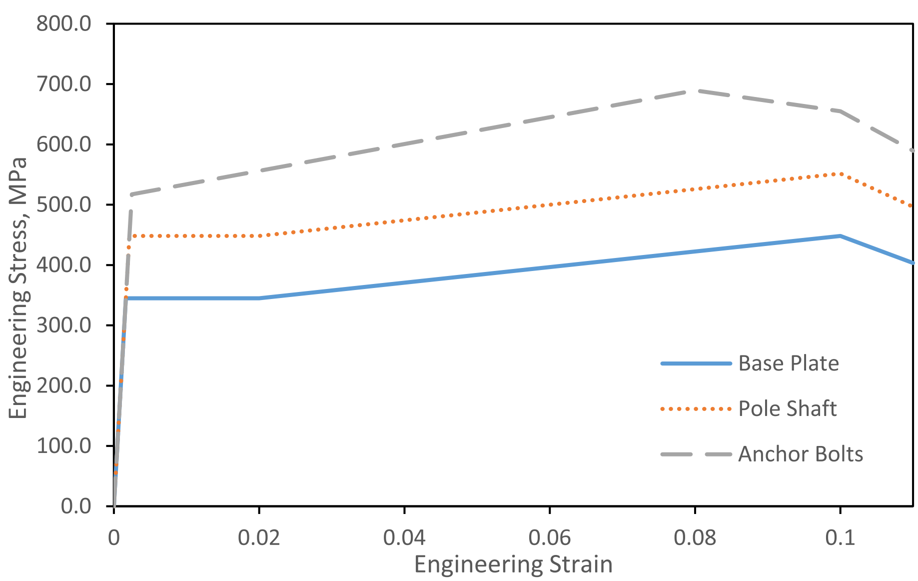


Fig. 3. Idealized Multilinear Steel Models Used to Model Base Plate Connection.
a) Details and Main Dimensions (in mm) of Tested Specimens

anchor bolts components and base plate.

2.2. 3D base plate connection model

The 3D geometry of the FE models is created employing the solid modeler ADINA-M available in the finite element package. Fig. 2 shows the basic connection model consisting of loading plate, shaft, fillet weld, base plate, and anchor bolts.

2.3. Material models

There are two steel material grades commonly used in the manufacturing of transmission steel poles in North America. The first steel grade is ASTM A572-GR65 and ASTM A572-GR50 which are used for the shaft and base plate, respectively. The yield strength of the two materials is 448 MPa for the former and 344 MPa for the later while the tensile strength of GR65 steel is 551 MPa and that of GR50 steel is 448 MPa. When it comes to anchor bolts, the most common material grade used in construction is ASTM A615 Grade 75 with a yield strength of 517 MPa and a tensile strength of 689 MPa.

For all steel materials, an idealized multi-linear stress-strain relation with von-Mises yield criterion and isotropic strain hardening is used. In plotting the engineering stress-strain relation, shown in Fig. 3, few points are evaluated based on the steel material utilized [3,7]. The first point is the yield point which is calculated assuming Young's modulus to be 210 GPa, beyond the yield point a yield plateau is assumed up to a strain of 0.02. This is followed by a strain hardening portion up to the ultimate stress value which is assumed at strain of 0.1 followed by a

Table 1
Material Property of the Tested Specimens [11].

Item	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)
12 mm Base Plate	284	461
16 mm Base Plate	288	464
M16 Anchors	437	669

declining branch till failure. Since the anchor bolt material does not have yielding plateau, the multi-linear curve is approximated and assumed to vary linearly from the yield point to the point defining the ultimate strength [3,4].

2.4. Applied load

Acting load is simulated by applying surface load to the rigid loading plate, the surface load is applied either in the global X direction or in the global Z direction to produce axial load or bending moment on the base plate connection respectively. In the case of polygonal shaft, the shaft is orientated as to have its top face parallel to the X-Y plane. The applied surface load is increased incrementally in a linear fashion following a pre-defined step function from zero to its full value utilizing the automatic stepping option in ADINA.

2.5. Contact pairs

The model includes three contact pairs between the base plate and anchor bolt components as follows:

i. Bottom face of top anchor bolt washer and top face of base plate
ii. Bottom face of base plate and the top face of the bottom anchor bolt washer
iii. Anchor bolt shaft and the side of the base plate bolt hole

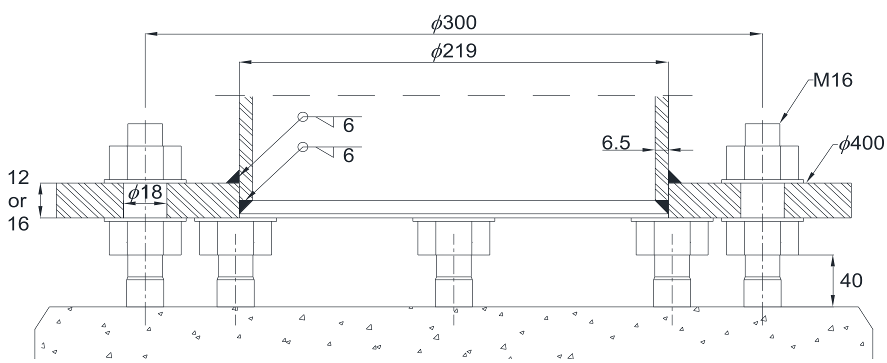
In all three contact pairs the base plate face that belongs to the pair being considered is set as the target while the other face is set as the contactor. The contact control is set to utilize the constraint function algorithm, considering large contact displacement formulation and without the use of post-impact corrections.

2.6. Boundary conditions

The bottom face of the anchor bolt group at the interface with reinforced concrete footing is restrained from movements in the three main orthogonal directions. It should be noted that symmetry is not considered in this model as to allow the application of non-symmetrical loading to the connection.

2.7. Tetrahedra and brick elements

The 10-node tetrahedra element is used to model the loading plate, shaft, weld, and anchor bolts while 20-node brick element is used to model the base plate both elements have three translational degrees of freedom per node. The thickness of the base plate is divided into six



a) Details and Main Dimensions (in mm) of Tested Specimens

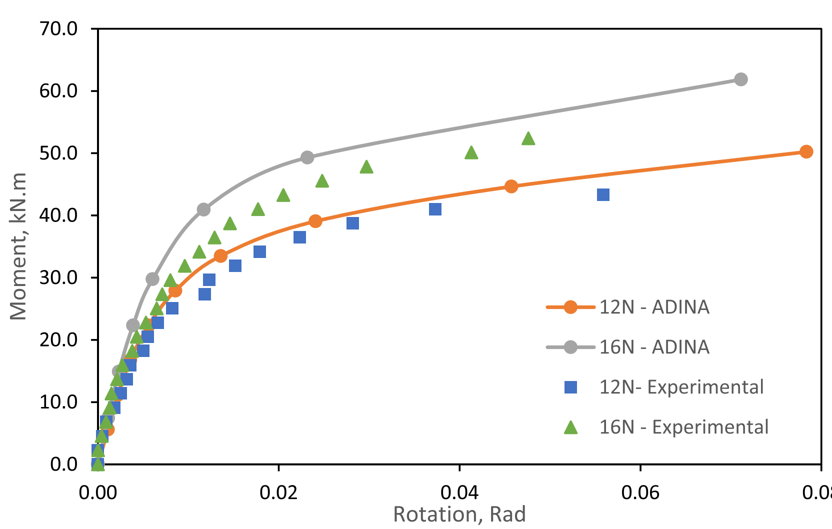


Fig. 4. Comparison between Experimental and FE Results of Base Plate Connections [5],

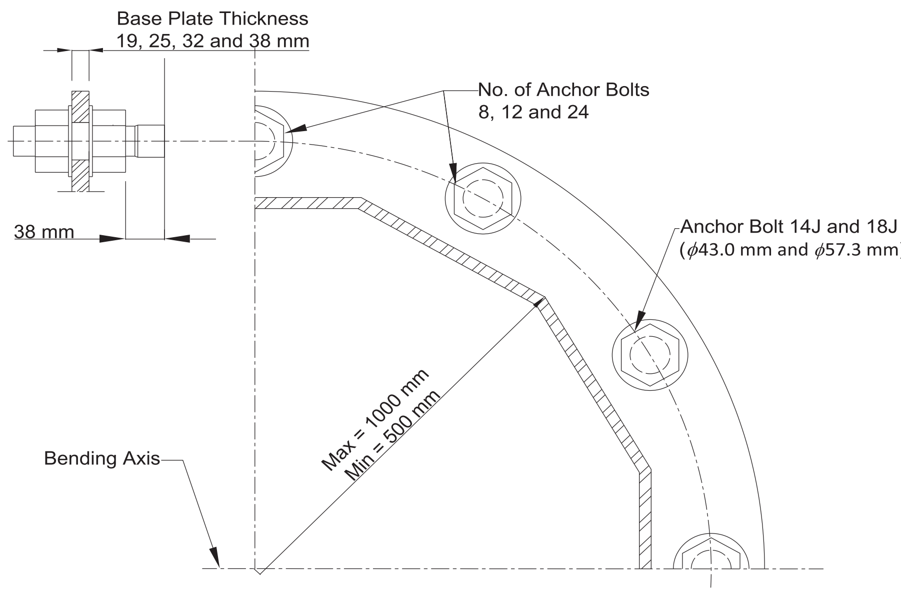


Fig. 5. Base Plate Outline and Design Variables.

Table 2
Finite Element Analysis Calculated Yield Loads for 12-Sided Shafts

a) Axial Compression

Specimen	Pole Diameter, mm	Plate Thickness, mm	No. of Anchor Bolts	Anchor Size	ADINA Yield Load, kN
1		19			1688
2	500	25	8	14 J	3000
3		19			2052
4	600	25	8	14 J	3672
5		25			3648
6	800	32	8	18 J	5760
7		25			3744
8	800	32	12	18 J	5760
9		32			7875
10	1000	38	24	18 J	10,800

b) Bending Moment

Specimen	Pole Diameter, mm	Plate Thickness, mm	No. of Anchor Bolts	Anchor Size	ADINA Yield Moment, kN.m
1		19			440
2	500	25	8	14 J	684
3		19			621
4	600	25	8	14 J	878
5		25			1152
6	800	32	8	18 J	1836
7		25			1200
8	800	32	12	18 J	2040
9		32			3488
10	1000	38	24	18 J	4350

elements to properly simulate and capture the bending behaviour of the plate [8–10]. It should be noted that the glue mesh option is utilized to connect the shaft and weld to the base plate top face due to the incompatibility of the two mesh generation techniques used in the modelling.

2.8. Bolt element option

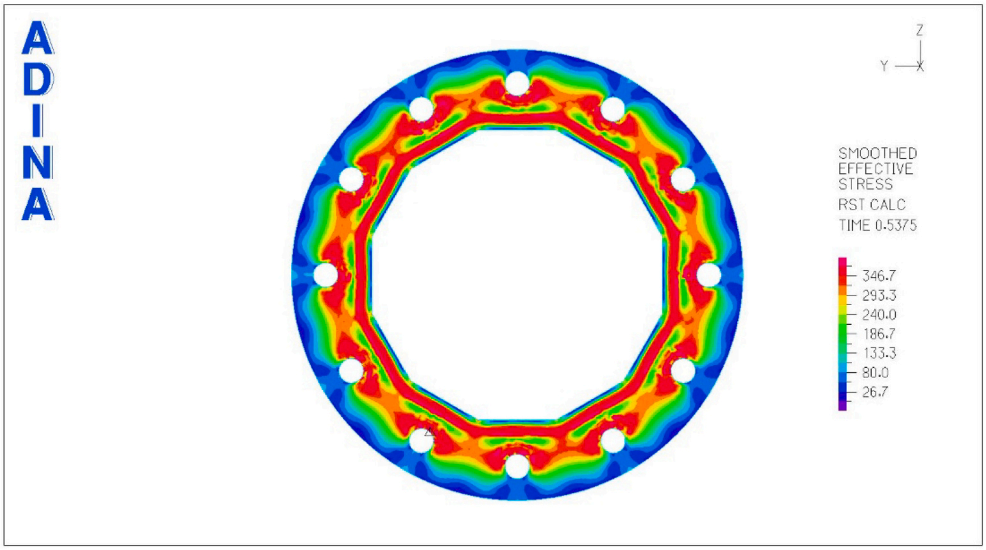
Top nut of the anchor bolt is typically tightened using turn of the nut method before installing a second top nut to secure the base plate connection. This method produces pretension load in the anchor bolt between the top and bottom nuts that is typically at the 20% level of the full pretension load. It is found numerically useful to model this pretension load since it improves the analysis convergence specially with the use of contact elements. Anchor bolt pretension load is set by invoking the bolt option in the anchor bolt element group and setting the pretension load value. The specified pretension load is then applied to the model in five equal steps prior to the application of the external load.

2.9. Analysis assumptions and convergence criteria

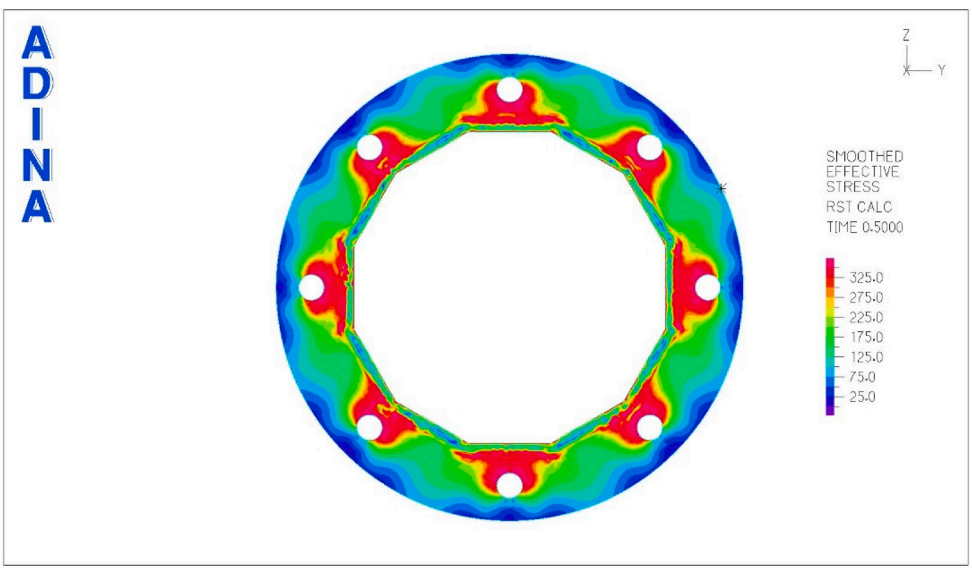
Incremental static analysis with large displacements and large strain formulation is used to simulate the behaviour of the base plate connection. Due to the utilization of non-linear material and contact groups two convergence criteria are specified these are energy and contact tolerances for which the software default values are used.

3. Validating the finite element model

Analysis assumptions, material models, elements selection, contact and boundary conditions used in creating the finite element model all need to be verified to ensure that the FE model can accurately capture the behaviour these connections. To accomplish this goal, two of the tested specimens reported in Ghareeb et al. [5] study are used to validate the bending behaviour of the FE model. The tested specimens reported in their study consisted of a 219 mm diameter 6.5 mm thick pipe welded to 400 mm diameter base plate through two lines of fillet welds 6 mm in size each. Base plate thicknesses used were 12 mm and 16 mm and are referred to as 12 N and 16 N, respectively. The specimens' base plates were connected to a reinforced concrete block using eight anchor bolts 16 mm in diameter arranged on a 300 mm diameter bolt circular and supported directly on levelling nuts. Material yield strength and ultimate strength of the different steel components of the two specimens are listed in Table 1. The specimens were loaded to failure by applying a single concentrated load 930 mm from the top face of the base plate. Load versus rotation responses of the tested specimens were recorded and reported in the study. The two specimens are modelled using ADINA software as described above and the moment rotation response of the simulated specimens are then plotted. A comparison between moment rotation response of the tested specimens and that of the FE simulations is shown in Fig. 4. Examining the results, it is clear that the FE analysis



a) Full Plate Yielding Mechanism



b) Zone Yielding Mechanism

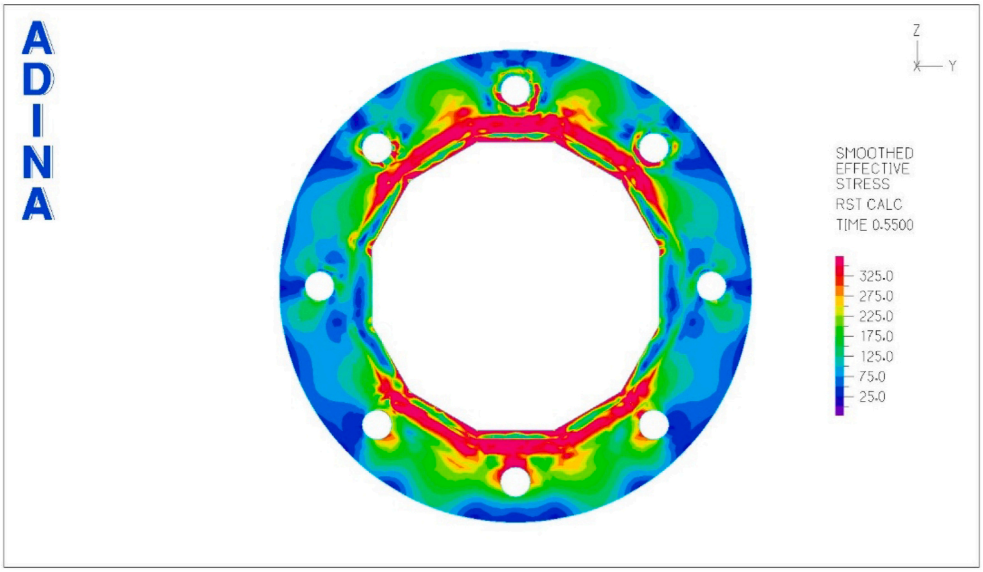
Fig. 6. Different Yielding Mechanisms for Plate Subjected to Axial Load.

can simulate the experimental behaviour of these specimens with good accuracy. Several methods can be used in determining the yield load for connections that do not exhibit a distinct yield load from the load-deflection or moment-rotation curves, such as the bi-linear approximation method [12] which is used in the current study. The difference between the yield load determined from the FE models using the bi-linear approximate method and that reported in the study is found to be 6% and 7% for 12 N and 16 N, respectively. There are several known factors inherent to the FM method contributing to the difference between experimental and the simulated results including the approximate material models used, and inherent rigidity of FE models in general. The finite element model developed in the current study have also neglected the interaction between anchor bolts and concrete block and a rigid connection is assumed at the bottom face of the anchor bolts. The study reported initial minor slippage of the top nut for during the testing of the 16 N specimen which contributed to the softer behaviour of the tested specimen compared to that of the FM model.

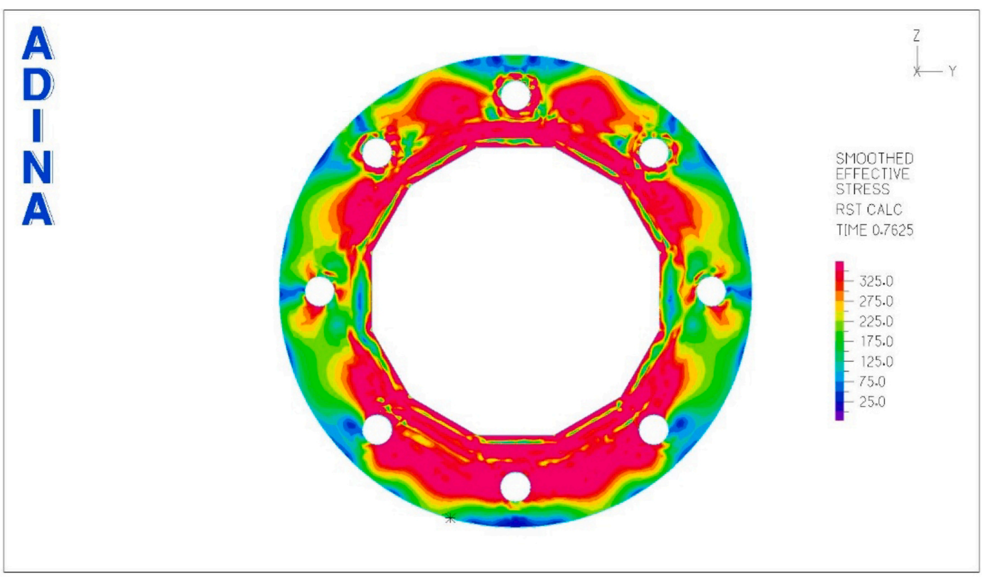
The current study covers the behaviour of the base plate connection under axial load as well, however, publish test results for such scenario are not readily available for validating of the model when subjected to axial load. Nevertheless, in a recent study Khedr [13]. used the finite element software ADINA to model flange plate connections with full contact under the effect of axial tension loads. In that study similar model was validated using published test results and was concluded that the FE model can accurately predict the failure mode as well as predicting the yield load with good accuracy.

4. Parametric investigation

Following the verification of the finite element model, the study is extended to perform a parametric investigation to examine the effect of changing few design parameters on the behaviour of the base plate and



a) at 70% My



b) at My

Fig. 7. Progression of Plate Yielding at Different Loading Steps for Plate Subjected to Bending Moment.

to calculate the axial load and bending moment causing the base plate to yield.

Shaft diameter, base plate thickness, number of anchor bolts and diameter of anchor bolts are all varied while other design parameters are kept constant. Shaft diameter is chosen such as to span a realistic range of diameters commonly used in transmission applications, other variables are selected to be compatible with the shaft. The following list summarizes the range of values used in the parametric study:

1. Shaft diameter: 500, 600, 800 and 1000 mm
2. Base plate thicknesses: 19, 25, 32 and 38 mm
3. Shaft cross section shape: 12-sided
4. Number of anchor bolts: 8,12 and 24
5. Anchor bolt diameter 14 J (43.0 mm or 1 ¾”) and 18 J (57.3 mm or 2 ¼”)
6. Bolt circle diameter: pole diameter plus 3 anchor bolt diameters
7. Outer plate diameter: bolt circle diameter plus 3 anchor bolt diameters

Fig. 5 shows general outline of the base plate connection with the design range of values used for each design parameter.

While individually varying the above listed parameters, steel grade for shaft, base plate and anchor bolts are kept unchanged. It should be noted that the combination of variables selected for the individual models are chosen as to not only cover a realistic range of steel transmission poles but to capture different base plate expected failure modes as well.

A total of twenty FE simulations resulting from varying the above design parameters for two different loading scenarios, axial load and bending moment, are performed. From each of these analyses, the axial

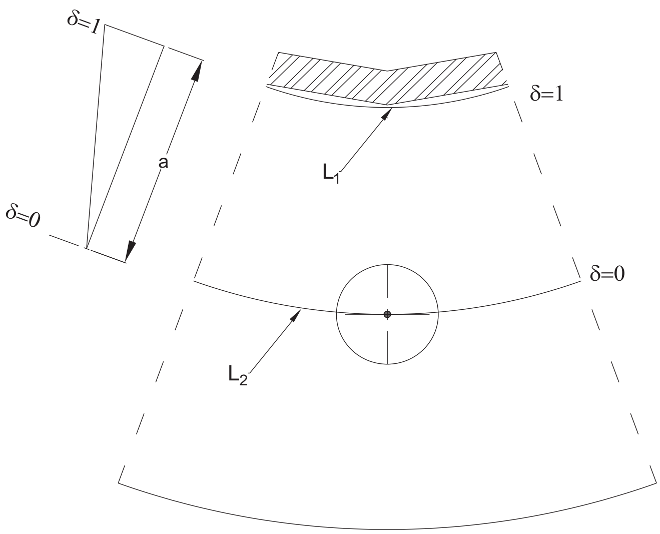


Fig. 8. Full Plate Yielding Mechanism Subjected to Axial Load.

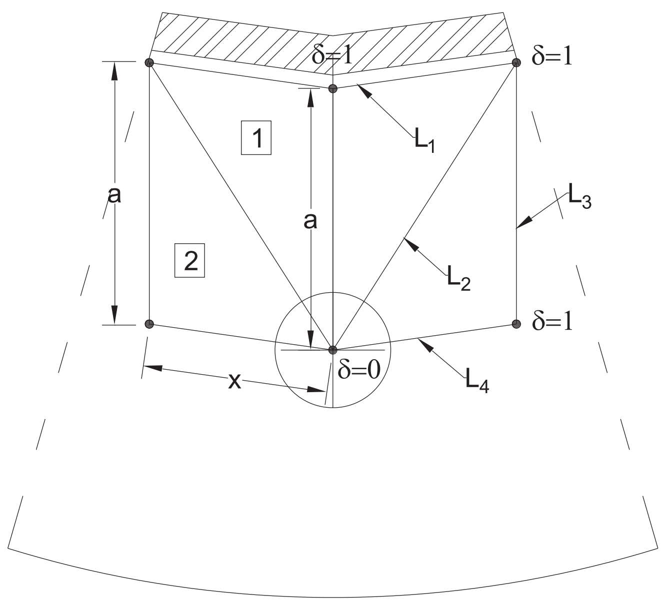


Fig. 9. Zone Yielding Mechanism Subjected to Axial Load.

load vs displacement or moment vs rotation curves, depending on load direction, are plotted to determine the load causing the connection to yield. The results of the analyses are presented in Table 2 for the 12-sided sections. It should be noted that the bi-linear approximation method used in determining the yield load is a graphical method that requires judgment in determining the yield load thus the estimated values listed in the tables below can slightly differ from one analyst to the other.

Smoothed effective stress distribution at the face of the base plate for all specimens which will be used in next section to aid in the development of the yield line mechanisms are also plotted. Sample of these stress distributions are presented in Figs. 6 and 7 for axial load and bending moment cases, respectively. It should be noted that the stresses developed in the shaft and the anchor bolts, not shown, are below their materials yield points. Fig. 6 shows the stress distribution for a base plate exhibiting a) complete yielding failure mode and b) zone yielding failure mode under the axial compression load case while Fig. 7 shows the progression of the plate yielding at two loading steps for a plate under bending moment.

5. Yield line analysis

The yield line method was developed more than sixty years ago to calculate the ultimate strength of reinforced concrete slabs. The method is based on the principle of virtual work where a solution is found by virtually equating the internal work required to accomplish the plastic deformation of a connected material to the virtual work performed by moving the external load through a distance compatible with the deformation of the connected material. Yield line analysis was used in numerous studies to evaluate capacities of numerous joint configurations under different loading conditions ([3,14–18]). To calculate the joint yield load, the method requires the failure pattern of the joint to be known in priori. Since for any given joint configuration there may be many valid yield line patterns and since the resulting yield load is an upper bound solution, it is necessary to find the proper pattern that gives the lowest load which provides results closest to the true yield load otherwise unsafe results may be obtained.

5.1. General

For the base plate connection under consideration and to obtain reliable results from the yield line method it is critical to make the right assumptions to the location of plastic hinges and the pattern of the assumed yield lines.

The performed external work for the axial load case is calculated using:

$$W_e = P \times \delta \tag{1}$$

While the external work performed for the bending moment case is given by:

$$W_e = M \times \alpha \tag{2}$$

Where:
P = axial load
δ = assumed base plate displacement
M = Bending moment
a = assumed base plate rotation

For both cases, the internal work done by the rotation of the yield lines is the sum of the work done by each individual yield line of the assumed pattern which is expressed as:

$$W_i = \sum_{i=0}^{m} m_p \times L_i \times \theta_i \tag{3}$$

Where:
m_p = plastic moment per unit length.
L_i = length of the i^{th} yield line.
θ_i = rotation of the i^{th} yield line.
i and m = yield line number and the total number of yield lines respectively.

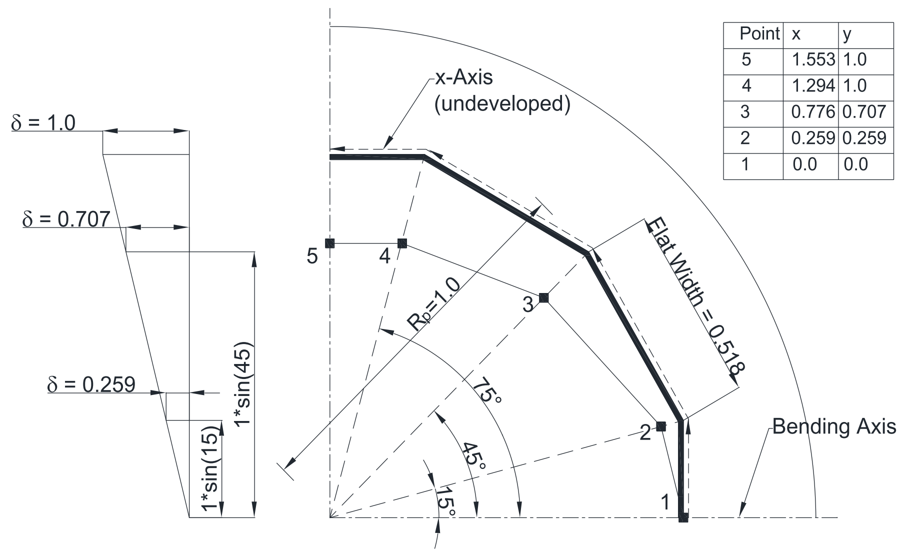
In the above equation the plastic moment per yield line unit length is given by:

$$m_p = f_y \times \frac{t^2}{4} \tag{4}$$

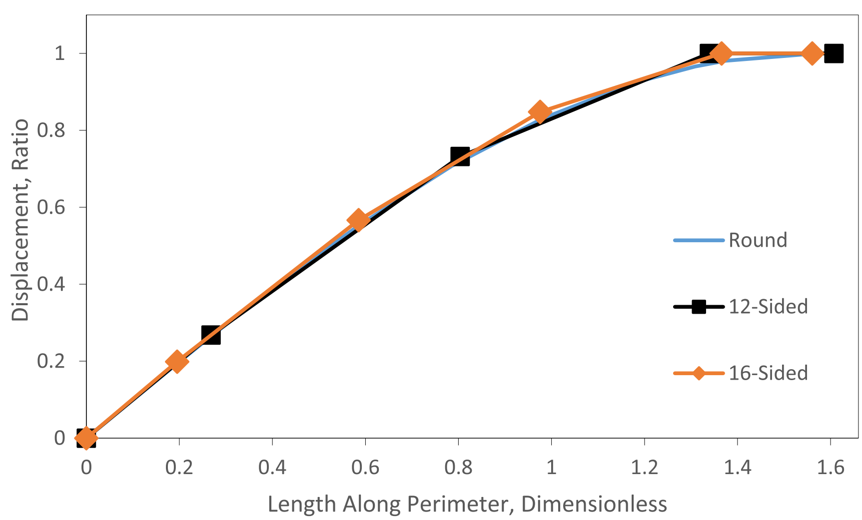
Where:
f_y = yield strength of the base plate material.
t = base plate thickness.

It should be noted that in designing steel transmission poles strength coordination is one of the principles designers must follow that requires the structure footing including the embedded anchor bolts not to fail prior to the failure of the pole itself. Thus, the internal work as presented in Eq. (3) shall not include the work done by the yielding of anchor bolts.

The connection strength is then calculated by equating the external



a) Displacement Calculations Along the Perimeter of 12-Seided Shaft



b) Comparison Between Displacements of Shafts with Different Shapes

Fig. 10. Displacement Along the Interface Between the Shaft and Base Plate.

work done by the applied load to the internal work done by yield lines.

$$W_e = W_i \tag{5}$$

In applying Eq. (5) all possible failure mechanisms or yield line patterns shall be consider from which the minimum internal work value is determined and thus the connection strength is calculated.

5.2. Plate yield mechanisms under axial load

Examining the failure mechanisms of the specimens included in the parametric investigation of the connection subjected to axial load, two possible mechanisms are identified and discussed in the following two subsections.

5.2.1. Full plate yielding mechanism

Full plate yielding mechanism assumes the formation of two circular yield lines in the plate as shown in Fig. 8. In this mechanism the yield line formed closest to the shaft, L_1, is assumed to be circular in shape and either surrounding the polygonal shaft apexes or coinciding with the circular shaft outer perimeter. Since anchor bolts are providing clamping support to the plate along the anchor bolt circle the second yield line coincides with the bolt circle with length, L_2. From the geometry of the connection and using Eq. (3), the internal work done by the base plate is given by:

$$W_i = \pi m_p D_p \frac{\delta}{a} + \pi m_p D_{bc} \frac{\delta}{a} \tag{6}$$

Where:

D_p = shaft diameter or twice the distance from center of the cross section to the vertex in case of polygonal cross section.

D_{bc} = anchor bolt circle diameter.

a = distance between shaft circumference and bolt circle.

Using Eqs. (1), (5) and (6) the axial force that causes this yield mechanism is determined from the following equation:

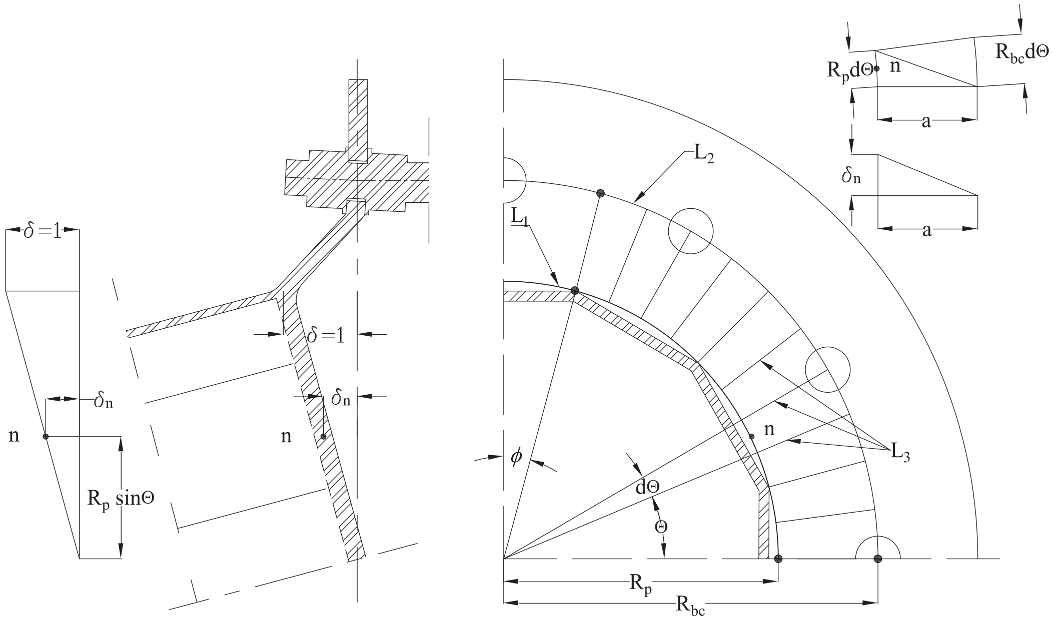


Fig. 11. Yield Line Mechanism for Base Plate Subjected to Bending Moment.

$$P_1 = \frac{\pi m_p}{a}\left(D_p + D_{bc}\right) \tag{7}$$

5.2.2. Zone yielding mechanism

Large diameter poles with fewer anchor bolts have large circumferential spacing between anchor bolts making it easier for a local mechanism around each anchor bolt to develop, like the stress distribution shown in Fig. 6 (b), instead of developing full plate yielding mechanism. Fig. 9 shows the simplified yield line mechanism associated with forming a zone mechanism in the base plate around each anchor bolt.

This yield line mechanism consists of four planes bounded by four yield lines namely L_1, L_2, L_3 and L_4 with the length L_3 known and equals to the distance a while the width of the zone is variable and equals 2×. The total internal work required for this mechanism to develop can be calculated in term of x as demonstrated in the following steps.

From the geometry of the zone and plane no. 1, the component of yield lines L_1 and L_2 projected on the axis of rotation, which coincides with L_1, is given by:

$$L_{1,2} = 4x \tag{8-a}$$

this component undergoes rotation $\theta_{1,\ 2}$ that is given by:

$$\theta_{1,2} = \frac{\delta}{a} \tag{8-b}$$

The component of yield lines L_2, L_3 and L_4 of the two planes no. 2 projected on the axis of rotation, which coincides with L_3, is given by:

$$L_{2,3,4} = 4a \tag{8-c}$$

this component undergoes rotation $\theta_{2,\ 3,\ 4}$ that is given by:

$$\theta_{2,3,4} = \frac{\delta}{x} \tag{8-d}$$

From the previous four equations, the internal work required for the zone mechanism to develop for a base plate connection with n anchor bolts for axial load can be calculated using:

$$W_i = nm_p\left(4x\frac{\delta}{a} + 4a\frac{\delta}{x}\right) \tag{8-e}$$

The minimum required work for the base plate to form this mechanism is then calculated by differentiating the internal work expression in Eq. (8-e) with respect to x and equating the result to zero, thus:

$$\frac{dW_i}{dx} = 0 = nm_p\delta\left(\frac{4}{a} - \frac{4a}{x^2}\right) \tag{9-a}$$

From which the value of x that is required to minimize the work is found to be:

$$x = a \tag{9-b}$$

Back substituting the value of x in Eq. (8-e) and using Eqs. (1) and (5), the force that will cause this mechanism to occur is therefore:

$$P_2 = 8nm_p \tag{10}$$

5.2.3. Connection axial yield load

The axial load that causes the connection to yield, P_y, is then calculated as the minimum of the two resistances P_1 and P_2 as calculated by Eqs. (7) and (10), respectively.

5.3. Plate yield mechanism under bending moment

When subjected to bending moment the cross section of the shaft at the interface with the base plate will deform about the bending axis. Using the assumption of the Euler–Bernoulli beam theory that plane section before deformation remains plane after deformation, the displacements along the interface can be calculated assuming the maximum displacement value equals to one. Fig. 10 (a) shows the displacement calculations along the perimeter of a 12-sided shaft having a radius, R_p equals to one. Similar calculations are performed for 16-sided and round shafts, the three curves are then plotted against the developed shaft perimeter as shown in Fig. 10 (b). This figure shows that for a shaft with polygonal cross section, the curve representing the displacement along the perimeter ends with a horizontal portion the length of which is given by ∅ Rp where the angle ∅ is a function of the number of shaft sides and equals zero for round shafts.

The proposed base plate yielding mechanism under bending moment, as shown in Fig. 11, assumes the formation of two circular yield lines, L_1 and L_2, along the circumference of the shaft and anchor

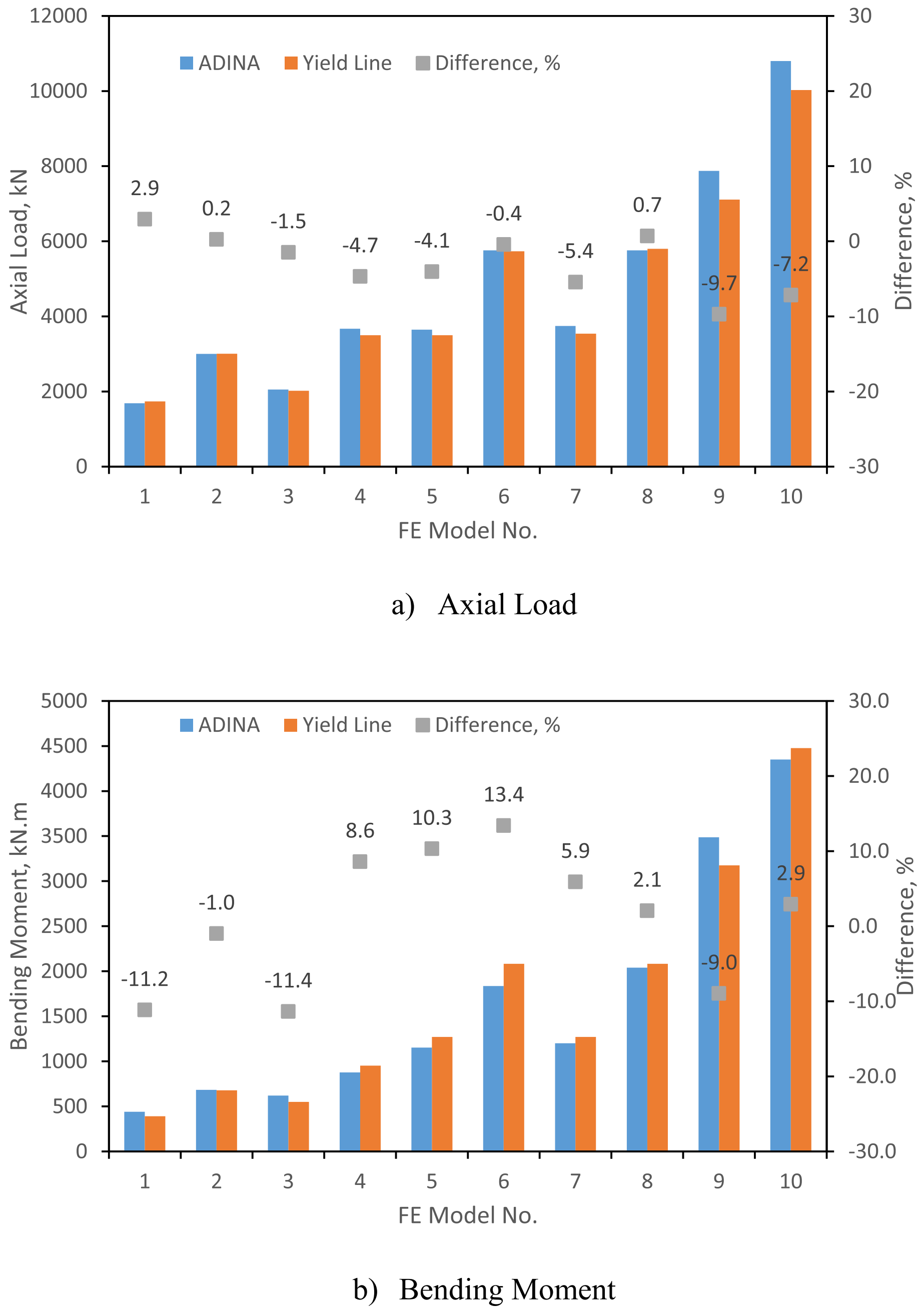


Fig. 12. Comparison between Yield Line Analysis Results and ADINA.

bolt circle, respectively. The displacement along yield line L_1 follows the displacement curves shown in Fig. 11 while the displacement along yield line L_2 equals to zero. In developing the yield line expression for shafts with polygonal cross sections, the yield line L_1 is assumed to form along the perimeter of a circle surrounding the polygonal cross section. In addition, a series yield lines pounded by L_1 and L_2 will also form and are referred to as yield lines L_3.

From the geometry of the deformed base plate, the displacement δ_n at any point n located on the shaft surface and making an angle θ from the positive X-axis is given by:

$\delta_n = \delta\ sin\theta$ for $0 \le \theta \le \frac{\pi}{2} - \phi$.

And

$\delta_n = 1$ for $\theta > \frac{\pi}{2} - \phi$

The internal work done by the formed yield lines L_1, L_2 and L_3 for one quarter of the base plate is given by the following three integrals:

$$W_{i1} = \int_0^{\frac{\pi}{2}-\phi} m_p \frac{\delta sin\theta}{a} R_P\, d\theta + \int_{\frac{\pi}{2}-\phi}^{\frac{\pi}{2}} m_p \frac{\delta}{a} R_P\, d\theta \tag{11-a}$$

$$W_{i2} = \int_0^{\frac{\pi}{2}-\phi} m_p \frac{\delta sin\theta}{a} R_{bc}\, d\theta + \int_{\frac{\pi}{2}-\phi}^{\frac{\pi}{2}} m_p \frac{\delta}{a} R_{bc}\, d\theta \tag{11-b}$$

$$W_{i3} = \int_0^{\frac{\pi}{2}-\phi} m_p \frac{\delta sin\theta}{a} R_{bc}\, d\theta \tag{11-c}$$

After performing the integration and noting that the above equations are for one quarter of the base plate, the total internal work is given by:

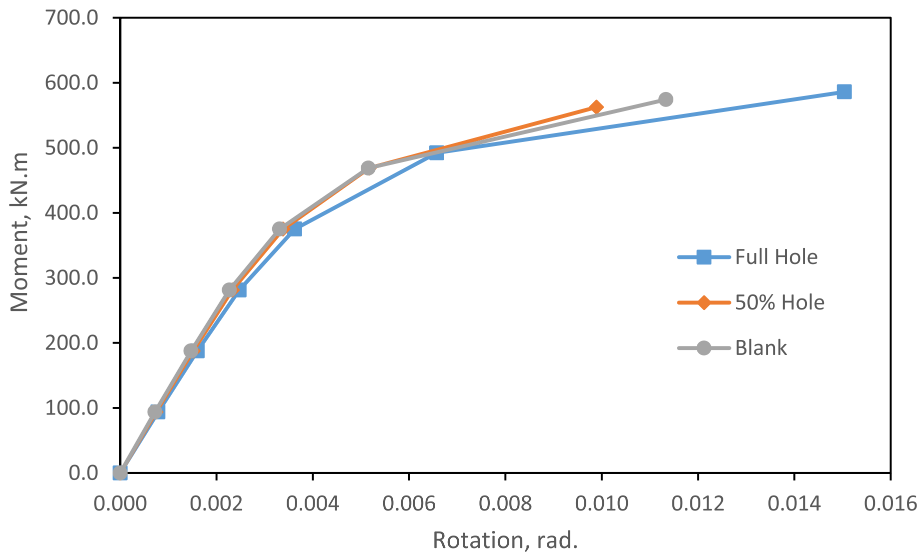


Fig. 13. Moment Rotation Curves for Specimen No. 1 with Different Centre Hole Diameter.

$$w_i = \frac{4m_pR_p\delta}{a}\left[1-cos\left(\frac{\pi}{2}-\varnothing\right)+\varnothing\right]+\frac{4m_pR_{bc}\delta}{a}\left[2-2\,cos\left(\frac{\pi}{2}-\varnothing\right)+\varnothing\right] \tag{12}$$

The external work exerted on the base plate connection is given by Eq. (2), noting that the rotation of the base plate connection a is given by $\frac{\delta}{R_P}$, the external work is calculated as:

$$W_e = M\frac{\delta}{R_P} \tag{13}$$

Equating the internal work to the external work, the bending moment that will cause the base plate to yield can be calculated from:

$$M_y = \frac{4m_pR_p^{\,2}}{R_{bc}-R_p}\left[1-cos\left(\frac{\pi}{2}-\varnothing\right)+\varnothing\right]+\frac{4m_pR_{bc}R_p}{R_{bc}-R_p}\left[2-2\,cos\left(\frac{\pi}{2}-\varnothing\right)+\varnothing\right] \tag{14}$$

Rewriting the above equation in terms of diameters, the yield moment is then given by:

$$M_y = \frac{2m_pD_p^{\,2}}{D_{bc}-D_p}\left[1-cos\left(\frac{\pi}{2}-\varnothing\right)+\varnothing\right]+\frac{2m_pD_{bc}D_p}{D_{bc}-D_p}\left[2-2\,cos\left(\frac{\pi}{2}-\varnothing\right)+\varnothing\right] \tag{15}$$

5.4. Connection design

In designing a circular base plate connection, anchor bolt diameter, number and bolt circle diameter are selected first. Bolt circle diameter is set as small as possible while allowing acceptable clearance between the nut corner and the reinforcement fillet weld which is chosen to be around 5 mm. The base plate diameter is then selected such that the distance between base plate edge and bolt circle diameter equals the distance between bolt circle diameter and pipe wall noting that base plate diameter has negligible impact on the connection strength [19]. This is then followed by choosing a proper trial base plate thickness, *t*, typically same order of magnitude to anchor bolt diameter. This is followed by calculating the axial load and bending moment causing the connection to yield P_y and M_y, respectively. An interaction equation shall then be used to check the adequacy of the chosen trial section to resist the combined effect of the applied axial load and bending moment using:

$$\frac{P}{P_y}+\frac{M}{M_y}\leq 1.0 \tag{18}$$

The interaction equation presented in Eq. (18) follows that is used by ASCE 48–19 design of anchor bolts equation.

6. Evaluation and discussion

The suggested yield line expressions are used to calculate the yield loads of the geometries included in the parametric study and reported in Table 2. These calculations are performed to assess the accuracy of these expression when used to predict the connections' yield axial load and yield bending moment. For each specimen the yield load is calculated then compared to yield load from the FE analysis and the percentage difference is then calculated and presented graphically in Fig. 12. In the two charts included in the figure, the left vertical axis is the yield load in kN, Fig. 12-a, or the yield moment in kN.m, Fig. 12-b, while the right vertical axis is the difference between the ADINA predicted yield axial load/bending moment and the calculated yield load/moment as a percentage of the ADINA yield axial load/ bending moment.

As can be seen from the figures the difference between the two values ranges from −11.4% to 13.4% with an average value of −0.9% for the base plate configurations analysed in this study. The source of this difference is contributed to the approximate nature of the yield line analysis method and to the fact that the determination of the yield load from FE analyses is achieved graphically from the load-deformation or moment-rotation curves which is approximate and based on judgment.

The verification of the presented yield line expressions is performed using the finite set of geometries included in the parametric study. It is important to discuss the limitation and the flexibility of the proposed design approach through discussing the effect of the number of anchor bolts, size of base plate centre hole, bolt circle diameter and number of shaft sides have on the applicability and accuracy of the proposed solution are presented.

6.1. Number of anchor bolts

The number of anchor bolts dictates the failure mode of base plates when subjected to axial load. The less bolts there are in the connection the more likely the design is controlled by the zone, or individual, failure mode.

For base plates connections subjected to bending moment, the presented yield line solution assumes that anchor bolts work as a group and therefore their number does not affect the final resistance of the connection. This validity of this assumption has been verified for connections having at least eight anchor bolts which is the minimum

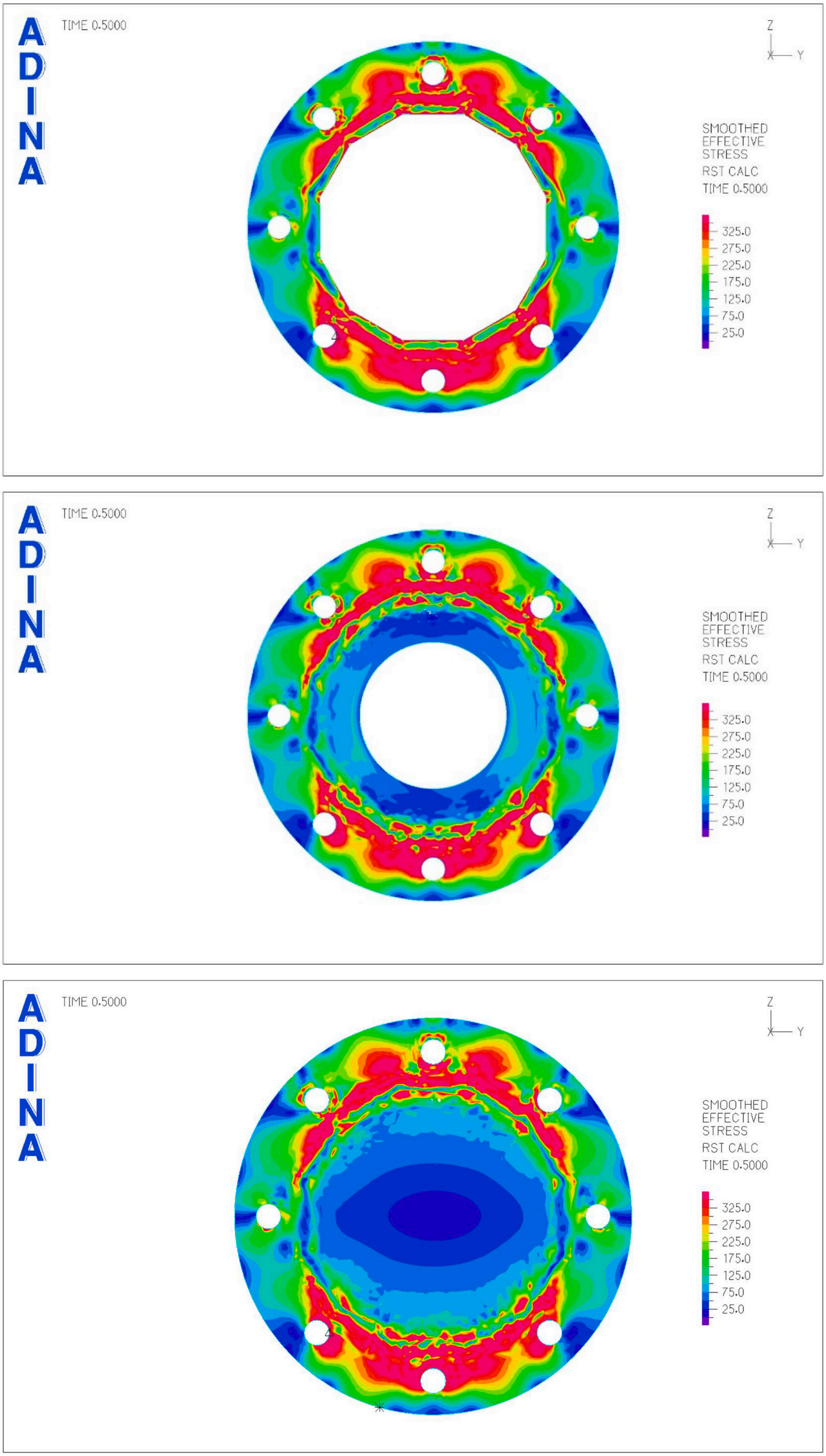


Fig. 14. Effective Stress Distribution for Same Model with Different Centre Hole Diameter.

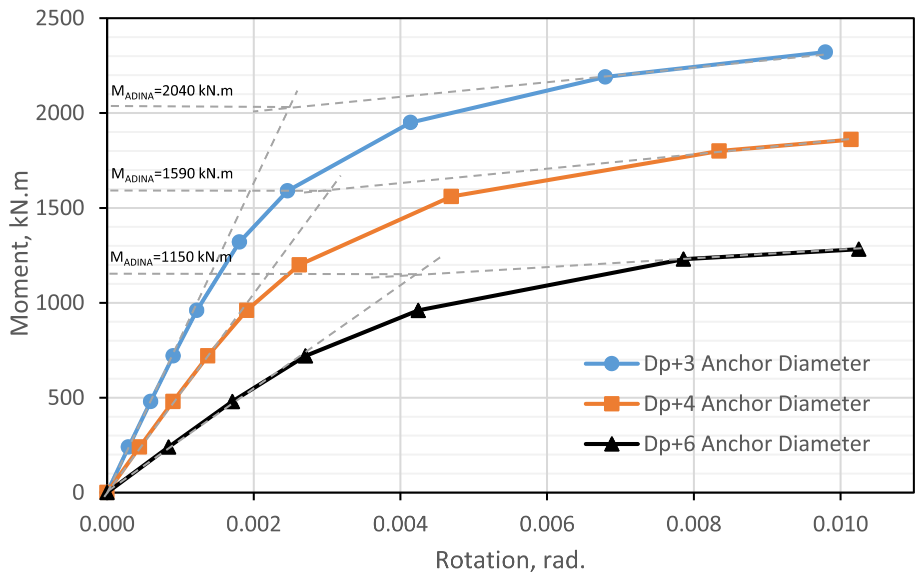


Fig. 15. Moment Rotation Curves for Specimen No. 8 with Different Bolt Circle Diameter.

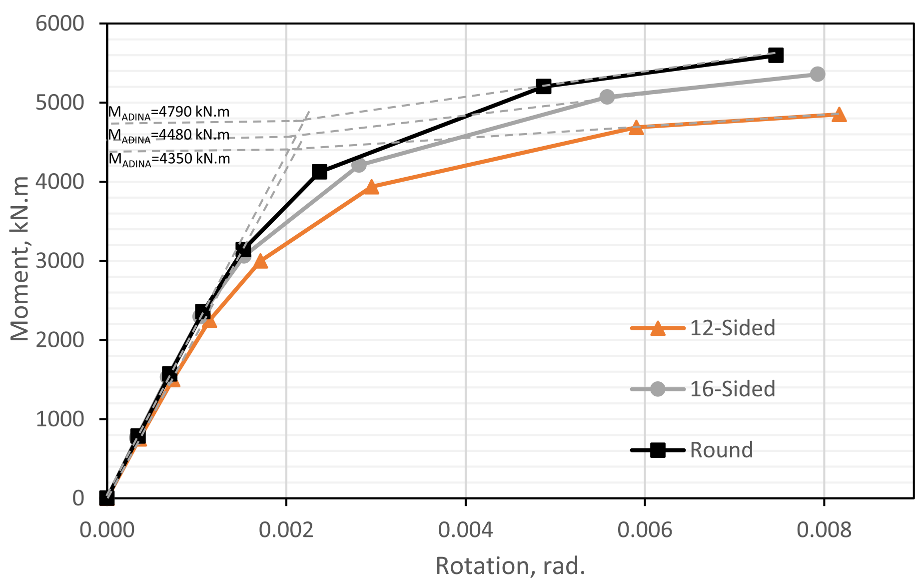


Fig. 16. Moment Rotation Curves for Specimen No. 10 with Different Number of Shaft Sides.

number used in parametric investigation. Base plates supported on lesser number of anchor bolts are expected to behave differently and the proposed expression can not be used for designing such plates without further validation.

6.2. Base plate hole size

Throughout the development of the yield line expressions presented in this work it is assumed that the base plate has a full hole that matches the inside shape of the shaft. However, the standard practice of some pole manufacturer is to detail the base plate with a centre hole that is smaller than the inside diameter of the shaft. It is therefore necessary to investigate the effect of the base plate hole size on the yield load and yield moment of the connection. This variation is studied by changing the inside hole diameter of different specimens included in the parametric study and examining the impact this change has on the axial and bending capacities of the connection. Fig. 13 shows comparison of the stress distribution for three cases, for specimen no. 1 of Table 2 under bending moment, while Fig. 14 shows the moment rotation curves developed for the three cases. As it can be seen from Fig. 13 the size of the hole does not affect the stress distribution in the zone of the base plate bounded by its edge and shaft outside wall. In addition, Fig. 14 shows that the size of the base plate hole has no impact on the moment rotation curve hence the load under which the connection will yield. The same results are obtained for other specimens and other load cases, and it is therefore concluded that the proposed yield line expressions can be used regardless of the base plate centre hole size.

6.3. Bolt circle diameter

The current work assumes a single yield line mechanism for the connections when subjected to bending moment. The limitation of this assumption, as indicated previously, is the minimum number of anchors for which the solution is verified. In addition, bolt circle diameter and hence bolt spacing is assumed constant throughout the work and set to be three times anchor diameter plus shaft diameter.

When the circumferential distance between the bolt increases the failure mechanism changes from group failure mechanism to zone failure mechanism which are both accounted for in the solution however, this is not the case for bending failure mechanism. To verify the validity of the proposed bending moment mechanism considering different bolt circle diameter specimen no. 8 of Table 2 is modified by increasing the diameter of bolt circle form shaft diameter plus 3 times anchor diameter to shaft diameter plus 4 times anchor diameter and shaft diameter plus 6 times anchor diameter. The two modified models are then analysed and the moment rotation curve of the three specimens are plotted as shown in Fig. 15. From this figure it the yield bending moment is determined and compared to the yield moment calculated using Eq. (15) and the difference is found to be 2.1%, 2.1% and 1.4% for the three specimens, respectively. This confirms that although the spacings between the anchors are increased, the yield line mechanism, as expected, holds correct and the derived equation for calculating the yield moment is producing accurate results.

6.4. Number of shaft sides

The development of the yield line mechanisms in this study is carried out assuming that the yield line closest to the shaft is circular in shape while the verification part of the work is completed using 12-sided shaft which is the common polygonal shape used by the transmission industry. The suitability of using Eq. (15) to calculate the yield moment of shafts having greater number of sides while maintain the same accuracy is verified using specimen no. 10 of Table 2 considering two additional cases, the first for 16-sided shaft while the second is for a shaft with circular cross section. These two additional variants are then analysed, and the three moment rotation curves are plotted as shown in Fig. 16 from which the yield moments are determined and compared to the yield moments resulting from Eq. (15). The calculated difference between the two sets of results is found to be 2.9%, 2.3% and 2.6% for the 12-sided, 16-sided, and circular shaft, respectively. The same exercise is repeated considering axial load where the calculated difference between the two sets of results is found to be −7.2%, −6.4% and − 13.7%, which is a good indicator that this equation can be used for shafts with higher number of sides.

7. Conclusions

A numerical investigation into the behaviour of steel transmission pole circular base plate connections supported directly on anchor bolts under the effects of axial load and bending moment is presented. The study is conducted using the nonlinear incremental finite element software ADINA implementing three dimensional solid elements, contact elements and bolt elements while considering material nonlinearities and contact-separation between anchor bolts and base plate. The assumptions used in developing the finite element model are verified through comparisons between the simulated load displacement response and that reported in published test results and are found to closely follow the experimental results with good estimate of the reported yield load.

A parametric study designed to span a wide range of practical base plate connection configurations is then conducted by varying shaft diameter, number of sides, plate thickness, anchor bolt diameter and number of anchor bolts. For each configuration the model is subjected to either axial load or bending moment and the load displacement or moment rotation of the connection response is plotted from which the load causing the base plate to yield under the applied load is determined.

The work progressed by presenting three expected yield line mechanisms for the base plate. Two of which considering the behaviour of the base plate under axial load while the third is considering the behaviour of the base plate when subject to bending moment. Axial load mechanisms covered the formation of discrete yield zones around each anchor as well as continuous yield lines around the shaft and the anchors bolt circle. The yield line mechanism considered for the bending moment case is for plate yielding considering the group of anchors. As a result of this study simple expressions for the yield line mechanisms are presented.

The yield loads calculated based on these expressions are then compared to the results of the FE investigation and it is found that the presented yield line expressions can predict the yield loads of the studied connections under axial and/or bending with good accuracy. The absolute maximum difference in axial load case and bending moment case is found to be 9.7% and 13.4% with an average error of −2.9% and 1.1%, respectively. The work also suggested the use of simple interaction equation to cover the case of a base plate subjected to a combined action of axial load and bending moment.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships

that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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