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Finite Element Modelling of Circular Steel Base Plate Connections

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ABSTRACT

The use of circular steel base plates having circular anchor bolts pattern is common in communication and traffic applications among many others. The lack of simple and accurate models for designing such connection plates, except for scattered trials, initiated the importance of further studying their behaviour. This paper presents a study for such connecting plates considering different parameters that have been analyzed using the Finite Element (FE) package ADINA. The finite element results were first verified through the use of experimental data available in the published literature. A parametric investigation was then carried out to numerically expand the experimental data in order to gain more insight into the behaviour of the base plates. The parameters changed in the numerical investigation included: base plate thickness; number of anchor bolts; bolt circle diameter; plate diameter; weld detail and stiffener presence. A simple design model based on yield line theory is then introduced and a comparison between yield moment predicted using it and ADINA results is presented.

Keywords

Circular base plate; finite element analysis; yield line analysis; anchor bolts

1. INTRODUCTION

Circular and polygonal hollow members are commonly used in wide range of applications such as long span space trusses, traffic signal and sign supports, lighting poles, telecommunication poles and towers to name a few. Round members are preferred in such applications due to their aesthetic appearance and low drag coefficients when compared to flat members. It is common to connect these members to each other or to the concrete footings using circular plates with circular bolt patterns. The connecting plates are either subjected to axial tension or compression forces as in the case of latticed tubular towers or subjected to bending moment and shear force as in the case of poles. When considering the connection to concrete footing two common details are used: supporting the base plate directly on anchor bolts levelling nuts or

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supporting it on non-shrink or expansive grout injected in the space between the base plate and the concrete footing.

Connection design in general and rectangular base plates in particular have been studied extensively with design guidelines available in design codes and published literature. However, this is not the case with circular base plate although their use is common. Published literature has come short of recommending a method for the design of these plates.

One of the first available published works covering the area of designing circular plate connections with circular bolt patterns was published in the 80's of the past century. Kato, B. and Hirose, R. [8] studied the maximum strength of circular tension flanged joints using high strength bolts. In their work yield line analysis was used in determining the maximum bending strength of the connecting flange when members are subjected to direct tension loads considering prying force. The strength resulting from the proposed yield line model was then compared to results obtained from 63 tests collected from the literature.

In two consecutive reports Cook et al. [4, 5] studied the problem of circular base plates subjected to bending moment. These studies aimed at evaluating the effect of the grout presence on the behaviour of lighting structures and to propose design criteria for such plates. However, the proposed design formula did not always give satisfactory results.

Ghareeb et al. [6, 7] conducted a research program at Benha University, to study the behaviour of circular base plates under the effect of bending moment. A test program was devised where a total of twelve specimens were tested to failure. In that study, two variables were considered: plate thickness and stiffeners presence. Other design variables were kept constant throughout the study. A design formula based on yield line approach, that gave acceptable results, was presented. However, the suggested formula was complicated and not suitable for hand calculations.

The current study aims at using FE analysis in performing a parametric study in order to assess the impact of changing some design parameters on the behaviour of circular base plate connection. The experimental data collected from the test program conducted in [6], was used as the mean for calibrating the FE model and thus extending the experimental investigation numerically [9, 10, 12]. A simple model based on yield line theory is then presented to estimate the yield moment of base plates.

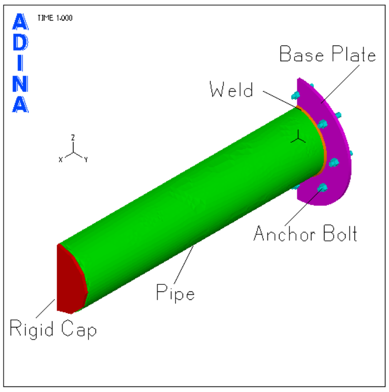
2. FINITE ELEMENT MODELS

General

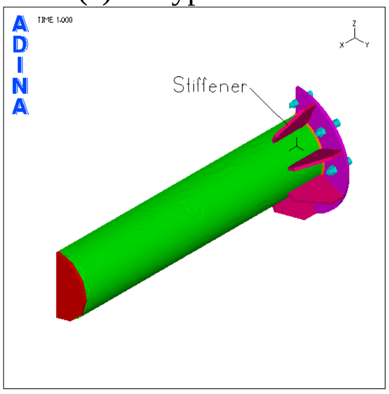
The behaviour of the specimens under investigation was simulated using 3D models implementing the general purpose nonlinear finite element program ADINA.

3D Steel Connection Model

The 3D models for the connection were created utilizing the solid modular ADINA-M available in the finite element package used. Fig. 1(a) shows the basic connection model that consists of rigid cape, pipe, weld, base plate and anchor bolts. In the model shown in Fig. 1(b), however, stiffeners are also included in the model. Throughout this paper, all models without stiffeners are referred to as N specimens while those containing stiffeners are assigned the letter S.



(a) N Type Model



(b) S Type Model

Fig. 1: General View of the 3-D Models Utilized in the Finite Element Analyses

Elements Used

The ADINA 8-node brick element with three translational degrees of freedom per node were utilized in the analyses to model the base plate, anchor bolts and nuts. Noting that bending effects in the base plate is significant, incompatible modes elements were used. A minimum of 4 elements across the thickness of the base plate were also used to be able to properly capture the bending behaviour of the plate [9, 15]. Rigid cap, pipe, weld and stiffeners, if present, were all modelled using tetrahedral elements. Face to face contact between the anchor bolts shanks and bolt holes, top nuts and base plate and levelling nuts and base plates were all considered assuming the base plate as the contactor and the other components as the target.

Steel Material Model

An idealized multi-linear stress-strain relation with von-Mises yield criterion and isotropic strain hardening is used in defining the steel material assigned to the main components constituting the FE model. When modelling the rigid cap, however, an elastic material model is considered to avoid numerical and conversion difficulties.

In defining the stress-strain relation, Fig. 2, four points are evaluated based on the steel material utilized. The first point is the yield point which is calculated assuming Young's modulus to be 206 GPa, beyond the yield point the tangential stiffness is assumed to be 4 GPa up to a strain of $11\varepsilon_y$. This is followed by a strain hardening portion up to the ultimate stress value which is assumed to occur at strain equals to 0.05. [3, 10].

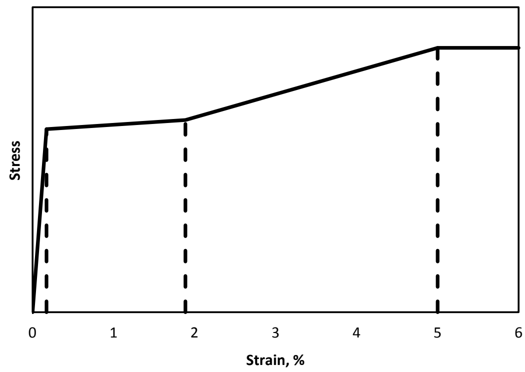


Fig. 2: Idealized Multi-Linear Steel Model Used in the FE Analyses

Boundary Conditions

In constructing the finite element model, symmetric nature of the specimen and the applied load was used in order to model only one half of the specimen and hence reduce the computation time. As the plane of symmetry is the X-Z plane as shown in Fig. 1 the y translations were restrained along the surface created by the cutting plane. The translations in the three main directions were restrained along the boundary surface between the anchor bolts and the concrete (not modelled).

Load

Single concentrated load acting in the negative Z direction was applied to the model with its point of application coinciding with the outer uppermost point of the rigid cap. The load was increased in a linear fashion from zero to full value in increments. The load was applied in increments using the automatic time stepping option in ADINA.

Analysis Assumptions and Convergence Criteria

Large displacements and large strain formulation is used in the analyses to simulate the actual behaviour of the tested specimens. Due to the non-linear nature of the problem which is present because of the materials non-linearity and the presence of contact elements, convergence criteria have to be specified. Two tolerances were specified namely energy tolerance is set to 1E-03 and contact tolerance is set to 5E-02 which is suggested in ADINA documentations.

3. VALIDATING THE FINITE ELEMENT MODEL USING EXPERIMENTAL RESULTS

It is important to make sure that the FE models are capable of capturing the overall behaviour of the tested specimens. Ghareeb et al. [6] tested specimens that are similar to those shown in Fig. 1. The specimens consisted of a 219mm diameter 6.5mm thick pipe connected to 400mm diameter base plate by two lines of fillet welds 6mm in size. The specimens were connected to concrete blocks using 8 anchor bolts arranged on bolt circle diameter of 300 mm and supported directly on levelling nuts. The three base plate thicknesses tested were 10, 12 and 16mm. The specimens were loaded by a single concentrated load 930 mm away from its supports.

A comparison between moment rotation response of the tested specimens reported in [6] and that of the FE simulation is shown in Fig. 3. Comparing the curves shown in Fig. 3, it is evident that the suggested FE models are capable of capturing the behaviour of these models with good accuracy.

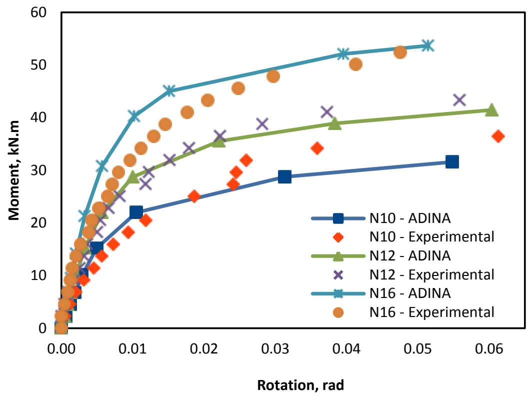


Fig. 3: Comparison between Experimental and FE Results of Non-Stiffened Base Plate Connections

The small deviation between the experimental and the finite element results are attributed to the following:

1. Inherent rigidity in FE models.
2. Test results for the steel materials used were not complete, only yield stress was included in the literature.
3. Interaction between anchor bolts and concrete block was not modelled, a rigid connection was assumed.

4. PARAMETRIC STUDY

After verifying the accuracy of the FE model, the experimental investigation was extended through performing a parametric study to examine the effect of changing several variables on the behaviour of such connections. The following parameters were varied:

1. Plate thickness
2. Number of anchor bolts
3. Bolt circle diameter
4. Outer plate diameter
5. Stiffeners presence and heights

While varying each of the above mentioned parameters, individually, the pipe cross section was taken as that in [6] and the steel used is S355. Base plate outer diameter was taken equal to 400mm and the steel material used was kept constant with a yield stress of f_y = 280 MPa and a tensile strength f_u = 460 MPa. Outer and inner weld sizes were both chosen as 5mm with a weld metal matching that of the base plate. Anchor bolts group consisted of 8 number 16mm in diameter arranged on a bolt circle diameter of 300 mm while the steel material used had a yield stress of f_y = 430 MPa and a tensile strength f_u = 540 MPa. It should be noted that throughout the remainder of this paper the above values are the default for the analyses.

As is important to examine the stress distribution in the different elements of the connections, Fig. 4 is constructed for two different specimens to show the stress-YY contours developed in the base plate, while Fig. 5 shows the effective stress in the double fillet welds. Examining the stress distributions shown in Fig. 4 it is apparent that the presence of stiffeners completely redistributed the stresses in the base plates with the area underneath the stiffeners having the highest stresses between each two consecutive anchor bolts. From Fig. 5 it can be seen that the double fillet welds do not share the stresses due to bending

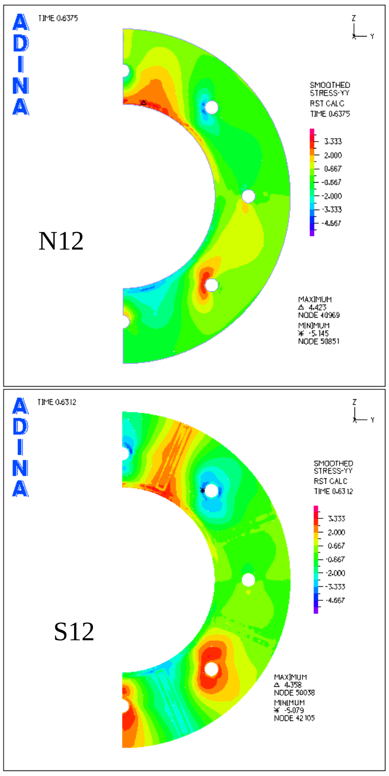


Fig. 4: Stress-YY Contours

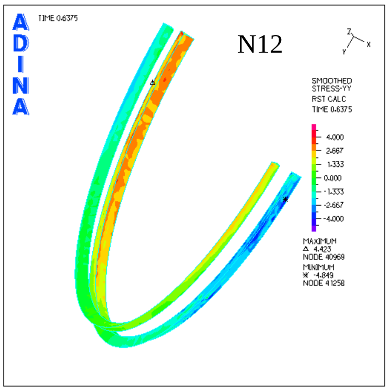


Fig. 5: Stress Distribution in Weld

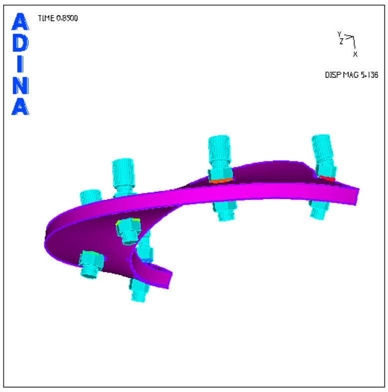


Fig. 6: Separation between Levelling Nuts and Lower Surface of Base Plate

moment equally as the outer weld line clearly transfers greater part of the applied moment to the base plate. Fig. 6 shows the separation between the levelling nuts and base plate surface at elevated loads which was reported in some of the specimens tested in [6].

After performing the finite element analyses, data from each analysis were collected and the moment rotation curves of such specimen were plotted. Fig. 7 shows the effect of changing the plate thickness on the connection behaviour while keeping the number of anchor bolts, bolts diameter, bolt circle diameter and plate diameter unchanged.

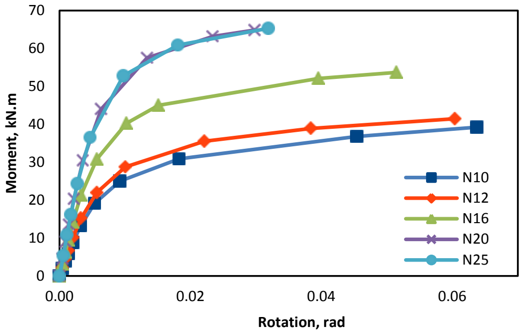


Fig. 7: Effect of Base Plate Thickness on the Moment Rotation Curve

Specimens with base plate thickness equals to 6, 8 and 10 mm have failed mainly due to yielding of the base plates, while thicker base plates, 20 and 25 mm, have failed due to reaching the plastic bending capacity of the group of anchor bolts. Plates with intermediate thicknesses, 12 and 16, have failed due to combination of both above mentioned reasons.

The effect of changing the number of bolts on the moment rotation response is shown in Fig. 8 for N10 as an example.

The moment rotation curves resulting from changing the base plate outer diameter and bolt circle diameter are shown in Figs. 9 and 10 for models N12 and N16 respectively.

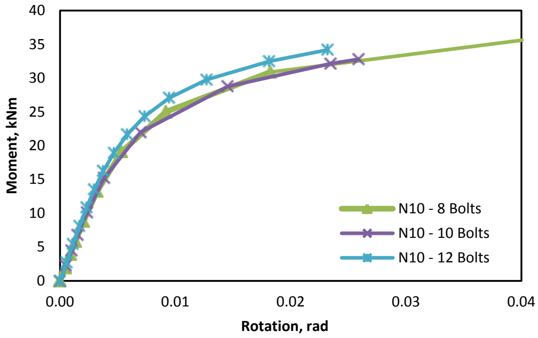


Fig.8: Effect of Number of Anchor Bolts on Moment Rotation Response of N10

It can be seen from Fig. 8 that the specimen behaviour is not controlled by the group of bolts and increasing the number of anchor bolts did not have significant effect on the overall behaviour of the connection.

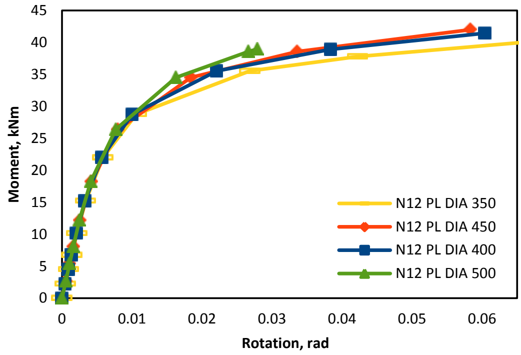


Fig. 9: Effect of Plate Diameter on Moment Rotation Response of N12

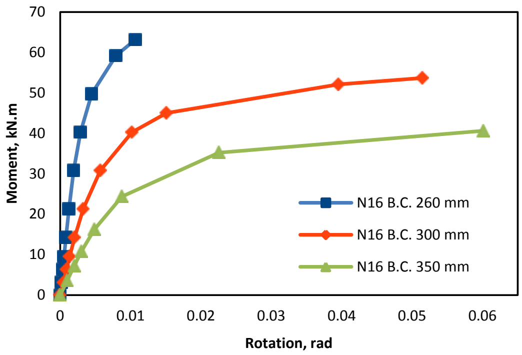


Fig. 10: Effect of Bolt Circle Diameter on Moment Rotation Response of N16

Examining the above mentioned figures it is concluded that changing the base plate outer diameter has insignificant effect on the connection behaviour. An increase of only 2% has been observed in the yield moment when the outer plate diameter was increased from 350 to 500 mm. Increasing bolt circle diameter from 300 to 350 mm has a more profound effect as 40% reduction in the base plate yield moment was found.

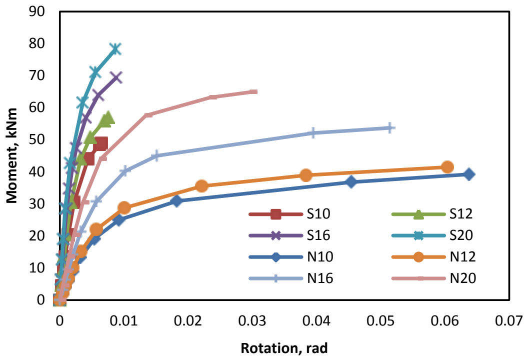


Fig. 11: Stiffened vs. Unstiffened Moment Rotation Response

The effect of adding stiffeners is shown in Fig. 11. It can be seen that stiffened connections exhibit a rotation of about one tenth of the unstiffened ones. However, the effect stiffeners have on the yield moment was not easily determined as failure mode, for flexible connections in particular, shifted from failure in the plate to a different mode of failure.

Stiffeners height was also varied and moment rotation curves were plotted for several heights and a comparison is shown in Fig. 12 for S10 connection.

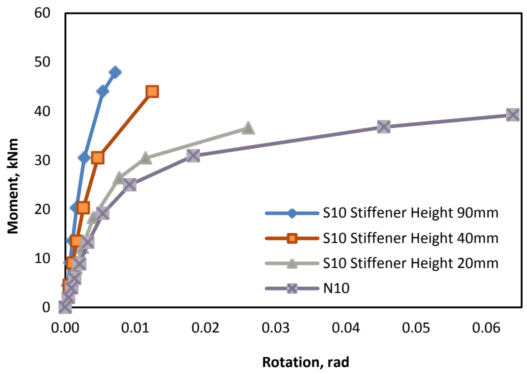
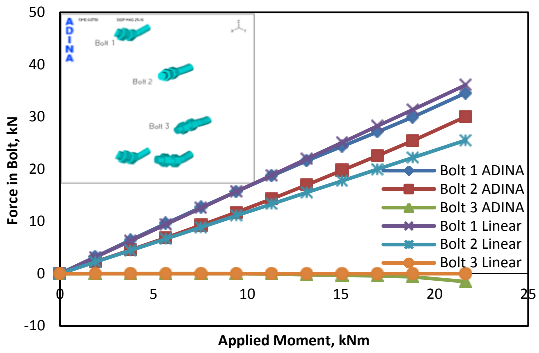


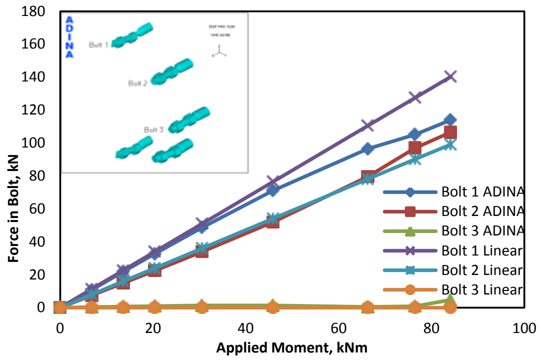
Fig. 12: Effect of Stiffener Height on the Moment Rotation Response

5. FORCE DISTRIBUTION IN ANCHOR BOLTS

The validity of assuming linear distribution while calculating axial forces developed in bolts was checked. Specimens N8 and S8 were chosen to ensure that flexible and rigid connections are both present in the comparison.



(a) Model N8



(b) Model S8

Fig. 13: Axial Force in Anchor Bolts

Fig. 13 shows the axial force in anchor bolts as calculated from FE analyses and those calculated using the applied bending moment and assuming elastic distribution of the forces.

Noting that the yield moment of the anchor bolts group was calculated to be 52 kNm, a good agreement between the two values of anchor bolts axial forces is observed up to the group's yield moment as can be seen in Fig. 13(b).

It is important to note that the deformed shape of anchor bolt group, shown in Fig. 13, was compared to the deformed shape of the anchor bolts group as reported in [6] and was found to be in agreement.

6. YIELD LINE ANALYSIS

Yield line analysis has been used in numerous studies to determine the yield moment of connecting plates [2, 5, 7, 8, 11, 13, 16]. In yield line analysis, it is crucial to make proper assumptions of the location of plastic hinges and the pattern of the assumed yield lines.

In developing the yield line pattern, the deflected shapes of base plates with different numbers of bolts were examined. The deflected shapes of base plates with different numbers of bolts suggested that plates with 6 bolts and above with any thickness undergo almost the same deformation pattern.

Fig. 14 shows the X-displacement contours for a 12 mm plate with different numbers of bolts. Fig. 15 shows the normalized X-displacement along the interface between the pipe and the inside of the plate for different thicknesses with 8 anchor bolts. Similar graphs were also constructed for plates supported on different numbers of anchor bolts and the same deformed pattern was found. It was concluded that the normalized deformed shape of the base plate is independent of its thickness as well as the number of anchor bolts (more than 6 bolts).

Based on the above observations the yield line mechanism shown in Fig. 16 is suggested along with the normalized displacement amplitude along the inside of the plate is also drawn.

The displacement shape is assumed to have two distinct regions, from angle 0 to $3\pi/8$, measured with the horizontal, with amplitude varying in a linear fashion from 0 to 1 and a second part from angle $3\pi/8$ to $\pi/2$ with constant amplitude equals to 1. It should be noted that the displacement amplitude along the bolt circle is set to 0.

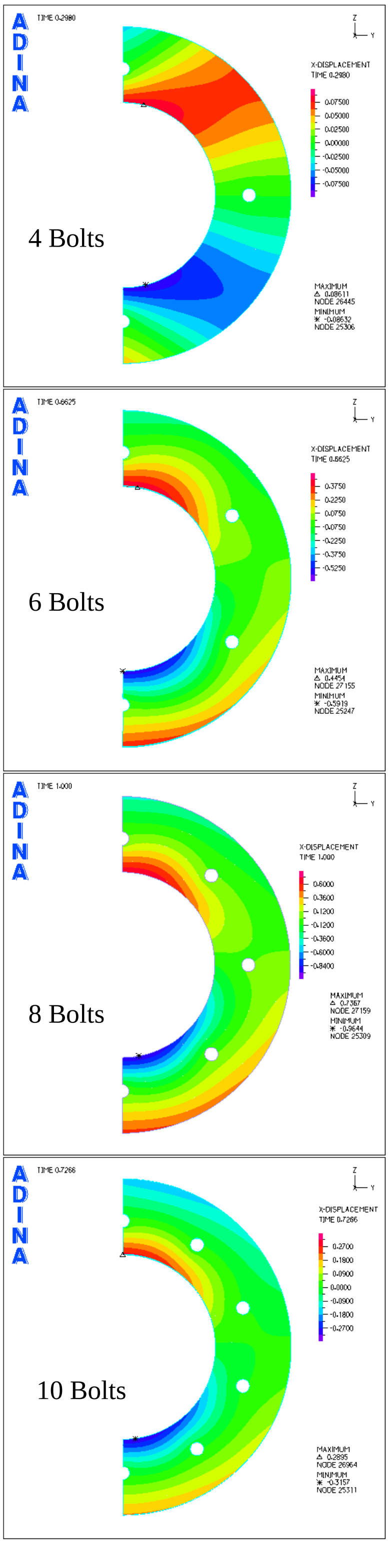


Fig. 14: X-Displacement Contours

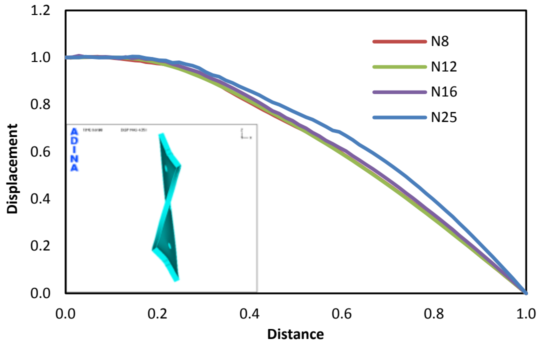


Fig. 15: Normalized X-Displacement along the Inside Face of the Base Plate

The principle of yield line states that the external work done by the applied forces must equal the internal work done by the rotation of the plates along the assumed yield lines. The external work done can be expressed as the applied moment multiplied by the rotation of the base plate caused by this moment:

$$W_{ext} = M\theta = \frac{M}{r_i} \quad (1)$$

The internal work done is the sum of the work done by the yield lines shown in Fig. 16. Therefore, the internal work done by the base plate is:

$$W_{int} = 4(W_1 + W_2 + W_3) \quad (2)$$

To account for the strain hardening effect on the ultimate moment capacity, the plastic moment per unit length, m_p, is calculated using a modified value of the yield stress as follows [11]:

$$f_p = \frac{f_y + 2f_u}{3} \quad (3)$$

The plastic moment per unit length of yield line is calculated using the following equation:

$$m_p = \frac{f_p {t_p}^2}{4} \quad (4)$$

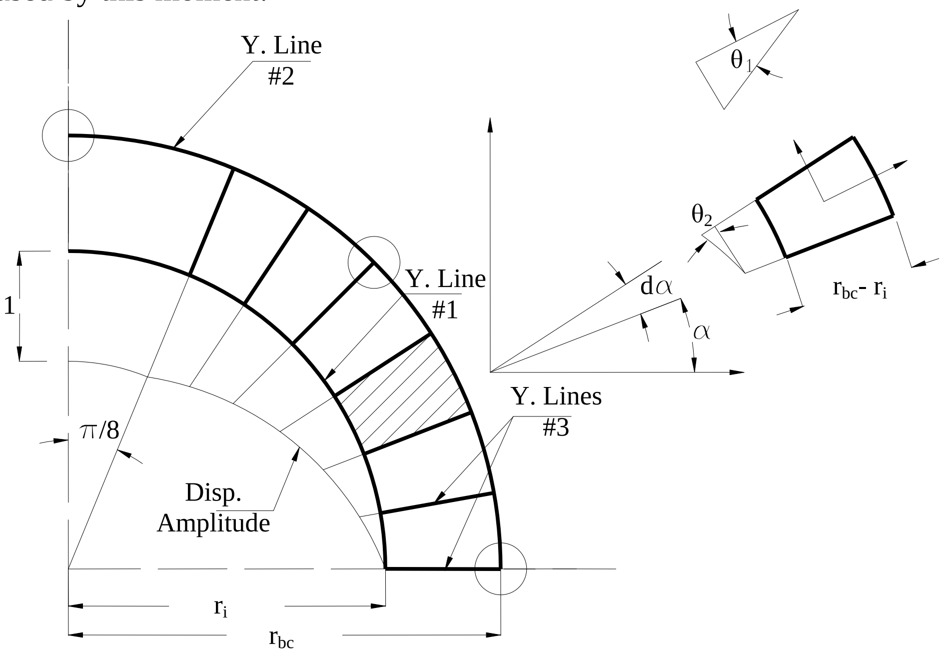


Fig. 16: Suggested Yield Line Mechanism

$$W_1 = m_p\left(\int_0^{\frac{3\pi}{8}} r_i . d\alpha . \frac{\frac{3}{8\pi}\alpha}{(r_{bc}-r_i)} + \int_{\frac{3\pi}{8}}^{\frac{\pi}{2}} r_i . d\alpha . \frac{1}{(r_{bc}-r_i)}\right)$$

Performing the integration and simplifying, the internal work done along yield line 1 is given by the following equation:

$$W_1 = \frac{5.\pi.m_p.r_i}{16(r_{bc}-r_i)} \quad (5)$$

Similarly, the internal work done along yield line 2 is given by:

$$W_2 = \frac{5.\pi.m_p.r_{bc}}{16(r_{bc}-r_i)} \quad (6)$$

Using the average deflection in zone bounded by the pipe with the maximum deflection at any given angle α and the bolt circle with zero deflection at the same angle, the rotation of yield lines number 3 is given by:

$$\theta_2 = \frac{\frac{1}{2}}{\frac{3\pi}{8}} = \frac{4}{3\pi} \quad (7)$$

Thus the internal work done by the group of yield lines designated by number 3 is given by:

$$W_3 = m_p \int_0^{\frac{3\pi}{8}} 2.(r_{bc} - r_i).\frac{4}{3\pi}.d\alpha$$

$$W_3 = 2.m_p.\frac{r_{bc}-r_i}{r_{bc}+r_i} \quad (8)$$

Equating the external work and the internal work done, the following equation is obtained:

$$M = f_p t_p^2.r_i.\left(\frac{5\pi}{16}.\frac{(r_{bc}+r_i)}{(r_{bc}-r_i)} + 2.\frac{(r_{bc}-r_i)}{(r_{bc}+r_i)}\right) \quad (9)$$

To evaluate the accuracy of Eq. 9, the yield moment of FE models was first determined by intersecting the initial slope and strain hardening slope of the models' moment rotation relation [14]. The relation between base plate thickness and the calculated yield moment was then plotted, Fig. 17, for a 300mm bolt circle diameter. The yield moment calculated using Eq. 9 was then plotted on the same graph as shown. Examining Fig. 17 it was found that for thin plates or flexible connections the predicted moment is in good agreement with the FE results. This was not the case for thicker plates or rigid connections as failure is attributed to either bolt group failure, weld failure or pipe failure or a combined failure mode. The bolt group plastic moment capacity was also plotted and found to control plates thicker than 16 mm.

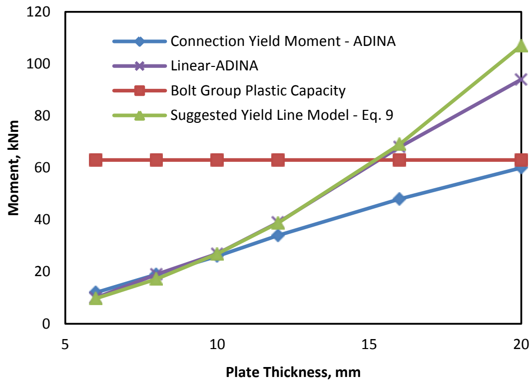


Fig. 17: Comparison between the Yield Moments of the Base Plate

Therefore, a new set of FE analyses was performed where all material models, except that of base plate, were assumed elastic. The yield moments were determined and plotted on Fig. 17, and referred to as Linear-ADINA. It is found that for plates of thickness up to 16 mm there is a perfect match when compared to Eq. 9. For thicker plates the difference is attributed to the nonlinearities resulting from the contact elements that may have affected the moment rotation relation of these models.

It is also necessary to use other expressions in evaluating the yield moment for comparison. The yield moments presented in [7] and Eq. 10 which was presented in [4] are used.

$$M = f_y t_p^2 \frac{r_{bc}.r_i}{r_{bc}-r_i} \quad (10)$$

Table 1 lists the yield moments for base plates having different dimensions using several methods: FE analyses as the reference value and referred to as M_{ADINA}, using Eq. 9, available in [7], and using Eq. 10. It was found that the yield moments calculated using the proposed Eq. 9 are in good agreement with those obtained using FE with an average ratio of $M_{Eq.9}/M_{ADINA}$ equals 1.02 and a standard deviation of 0.05.

Table 1: Comparison between Predicted Yield Moments Using Several Methods

t_p mm	r_i mm	r_{bc} mm	f_y MPa	f_u MPa	M_{ADINA} kNm	$M_{Eq.9}$ kNm	$M_{[7]}$	$M_{Eq.10}$ kNm	$M_{Eq.9}/M_{ADINA}$
10	110	150	284	430	27	27	25	18	1.00
12	110	150	284	430	39	39	40	27	1.00
16	110	150	284	430	68	69	63	47	1.01
20	110	150	284	430	94	107	N/A	74	1.14
12	110	175	284	430	26	26	N/A	28	1.00
16	110	175	284	430	49	48	N/A	50	0.96
20	110	175	284	430	69	73	N/A	78	1.06
								Average	1.02
								St. Dev.	0.05

7. CONCLUSIONS

A numerical investigation of the behaviour of circular base plates supported on anchor bolts levelling nuts arranged in a circular pattern was presented. The FE program ADINA was used in the study implementing three dimensional solid elements while considering material non-linearity and contact-separation between base plate and anchor bolts.

A parametric investigation was carried out where several variables were changed to examine their effect on the connection behaviour. It was found that, if not controlled by anchor bolts strength, the number of anchor bolts has no bearing on the base plate yield moment. It was also observed that outer weld was always more stressed than inner weld. In addition, it was found that the presence of stiffeners have a significant effect in restraining the rotation of the connection. Stiffened base plates were found to exhibit greater strength compared to non-stiffened base plates with the same thickness.

A simple expression for predicting the yield moment of this type of base plates based on yield line was suggested. This expression gave acceptable predictions when compared to FE results.

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ملخص البحث

تستخدم ألواح الأرتكاز الدائرية المثبتة بجوايط مرتبة بطريقة دائريه بكثرة فى التطبيقات الخاصة بأبراج الأتصالات ولوحات إعلانات المرور بالإضافة لتطبيقات أخرى. نظراً لعدم وجود نماذج بسيطة ودقيقة من أجل تصميم ألواح الأرتكاز هذة باستثناء بعض المحاولات المبعثرة التى أبدت على أهمية مواصلة دراسة سلوكها. لذلك تم عمل دراسة بحثية باراميتريه لهذه الوصلة باستخدام طريقة العناصر المحددة (بأستخدام برنامج الحاسب الآلى حزمة برنامج ADINA). فى هذا البحث تم دراسة عدة عوامل مثل سمك ألواح الأرتكاز, عدد جوايط التثبيت, قطر دائره التثبيت, قطر لوح الارتكاز, وجود أعصاب تقوية لألواح الارتكاز او بدون. تم أولا مراجعة نتائج طريقة العناصر المحددة بالنتائج المعمليه الموجوده فى الأبحاث المنشوره و تم مقارنة عزوم الخضوع المتوقعة بأستخدام نتائج نظرية خطوط الخضوع وبرنامج ADINA.