EVALUATION OF VARIABLE STIFFNESS OF WIND TURBINE TOWER WITH CONSIDERATION OF FLANGE - JOINT SEPARATION BY USING FEM ANALYSIS

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Abstract - Development of clean renewable energies is necessary due to the global warming. Among them, the number of wind turbines is on the increase because the development of wind power has been noticed. Since characteristic weather conditions and terrain conditions in Japan cause great damage to wind turbines, design guidelines (Japan Society of Civil Engineers 2007, 2010) were published. In the GL Wind 2003 (Europe), the maximum wind speed verifying the fatigue strength of high-strength bolts of wind turbines is set to 0.7 time of the design wind speed and the frequency of appearance of high wind speed is extremely low. Fatigue damages due to high wind speed can be ignored. On the other hand, the frequency of appearance of high wind speed in Japan is much higher. It is very important to understand the responses of wind turbines and the fatigue behaviors throughout the operation periods. The loading conditions of tower's flange - joints during high wind speed have not been clarified yet. Therefore, it is necessary to evaluate the fatigue strength in a strong wind condition up to the design wind speed and the response of wind turbine tower with the consideration of joint separation for establishing the design methods. In this study, we evaluate it in two steps. Firstly, a model of a tower using high-strength bolts at flange joints is created and FEM analyses are performed. Then, stiffness of the flange joint is determined in order to model variable stiffness of the flange joints with considering the whole wind turbine tower.

Key words - wind turbine; Flange – joint; bolt; separation; stiffness.

1. Introduction

It is necessary to determine the axial force in the bolt rather than tensile force acting on the bolt when performing the evaluation of fatigue damage of the bolt. Because when evaluating cumulative fatigue damage, fatigue limit curve has been used in Schmidt - Neuper diagram (Figure 1), not the external forces of the bolts, axial forces actually occur inside of the bolts are necessary to be determined (Guide Line Wind 2003). As Schmidt - Neuper's evaluation formula (S-N formula), we can calculate the axial force of one bolt during operation period.

From the FEM analysis result we can verify and compare between calculated results using the formula and analytical results from which to draw conclusions about the reliability of the results (Figure 2).

$$\mathrm{T_p} = \begin{cases} \mathrm{T_v + pT_s} & \mathrm{T_s \le T_{sI}} \\ \mathrm{T_v + pT_{sI} + (\lambda T_{sII} - T_v - pT_{sI})\frac{T_s - T_{sI}}{T_{sII} - T_{sI}}} & \mathrm{T_{sI} < T_s < T_{sII}} \\ \lambda \mathrm{T_s} & \mathrm{T_{sII} < T_s} \end{cases} \quad (1)$$

$$\mathrm{T_{sI}} = \mathrm{T_v} \times \frac{(\mathrm{e} - 0.5\mathrm{g})}{\mathrm{e+g}} \quad (2)$$

$$\mathrm{T_{sII}} = \frac{\mathrm{T_v}}{\lambda \times \mathrm{q}} \quad (3)$$

$$\mathrm{T_v} = \mathrm{N_0} = 0.75 \times \sigma_y \times \mathrm{A_e} \quad (4)$$

$$\mathrm{q} = 1 - \mathrm{p} (5)$$

$$\mathrm{p} = \frac{\mathrm{C_b}}{\mathrm{C_b + C_c}} (6)$$

$$\lambda = \left(1 + \frac{\mathrm{g}}{0.7\mathrm{e}}\right) \quad (7)$$

$$C_f = \frac{E}{2t_F}\left\{\frac{\pi}{4} + \frac{\pi}{8} d_w (D_A - d_w)\left[\left(\sqrt[3]{\frac{2t_F \cdot d_w}{D_A^2}} + 1\right)^2 - 1\right]\right\} (8)$$

$$C_w = \frac{\pi \cdot E \cdot (d_{wo} - d_{wi})^2}{4t_w} \quad (9)$$

Here:

- $\mathrm{T_p}$: Axial force of bolt;
- $\mathrm{T_s}$: Tensile force acting on the tubular body at one respective bolt;
- $\mathrm{N_0}$: Design bolt tension;
- $\mathrm{T_v}$: Initial tension of bolt;
- e : Distance between the end of flange bolt and center of bolt;
- g : Distance between center of plate of tubular body and center of bolt;
- $\mathrm{C_b}$: Tensile spring constant of bolt;
- $\mathrm{C_c}$: Compressive spring constant of flange;
- P : The ratio of forces inside and outside;
- λ : Compensated leverage ratio;
- σ_y : Yield strength of bolt;
- $\mathrm{A_e}$: Effective cross-sectional area of screw;
- C_f : Compressive spring constant of flange;
- C_w : Compressive spring constant of washer;
- d_s : Shaft diameter of bolt;
- d_w : Load bearing surface diameter;
- d_h : Diameter of the bolt hole;
- d_{wo} : Outside diameter of washer;
- d_{wi} : Inside diameter of washer;
- t_F : Width of flange;
- t_w : Width of washer;
- E : Young modulus of steel;
- D_A : Bolt pitch.

This calculation formula from (1) to (9) is suitable for a cylindrical tower, wind turbine and chimney with L type flange joint without an inner rib. The axial forces which be determined by S-N formula are the almost the same results when compare with Petersen's experimental results and FEM analysis results of three-dimensional model.(GL for Design of Wind turbine Support Structures and Foundations, p.298). This configuration of the calculation formula is simple, it is easy to handle.

Collapse mechanism 1: Non-deformation.

Collapse mechanism 2: Tensile force in bolt exceed the allowable tensile force by the lever reaction force (Pr).

Plastic hinge occurs at local of tubular body.

Collapse mechanism 3: Plastic hinge occurs at local of tubular body and the hole portion of bolt. The bolt stress exceeded the Yield point stress.

With the development of enlarged wind turbine, people began using the flange joints which exceed the scope of the guideline formula with FEM analysis in basically. So they perform to revise the strength evaluation formula. With this concept Petersen's evaluation (GL for Design of Wind turbine Support Structures and Foundations, p.267, 268) formula has been used widely. In this formula Petersen has considered that allowable yield strength of flange have been divided in three collapse mechanism (Figure 3).

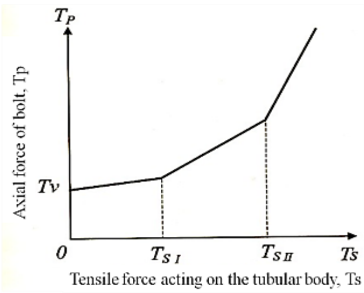

Figure 1. *Schmidt –Neuper diagram*

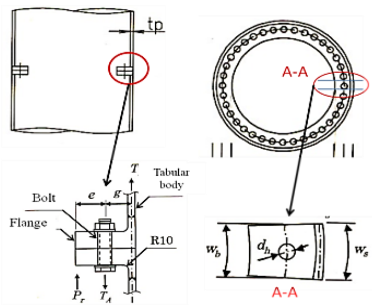

Figure 2. *Detailed diagram of L-flange joint*

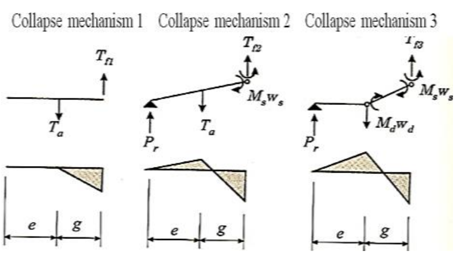

Figure 3. *Petersen's collapse mechanism*

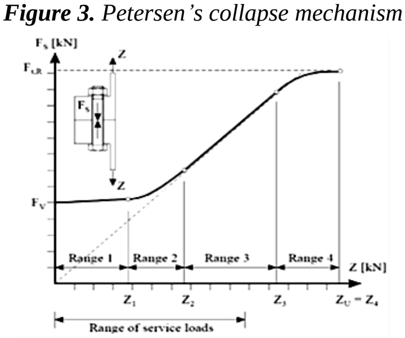

Figure 4. *Non linear relationships between bolt force and applied load in the shell of tubular towers with flange connections*

The failure at the ultimate limit state can either appear by exceeding the resistance in the bolt, in the flange or both at the same time, which are called failure modes 1 – 3 by Petersen, see Figure 3. Seidel then differentiates between failure in the flange at the axis of the bolt or below the washer and called these failure modes 4 and 5 instead of 3.

For fatigue the damage of the bolt is the resistance controlling problem. However, this cannot exclusively be the limit for the design. As Figure 4 shows, the relationship between the forces in the bolt and the applied tension in the tower shells is non linear and can be divided into four ranges. Usually, the existing service and fatigue loads occur in ranges one to three.

4 Ranges were proposed by Seidel:

Range 1: Approx, linear curve, stresses between flanges are reduced while contact zone is closed.

Range 2: Successive opening of flanges.

Range 3: Open connection with slope depending on loads geometry.

Range 4: Plastification of bolts and/or flange until failure of the connections.

The stresses in the bolt depend nonlinearly on the tension force as the connection has pre-loaded bolts. A typical graph showing the nonlinear correlation of external load and tension force in the bolt is shown in Figure 4. The behavior is similar for the bending moment in the bolt. The complex nonlinear behavior of this eccentrically loaded connection and high dynamic loads of wind turbines with more then10^9 load cycles in 20 years demand for safe and economic design methods. Experimental investigations on flange segments in the laboratory and in operating wind turbines have been performed to calibrate the results of simplified calculation models against experimental values. Additionally, a 3D finite element model has been used to extend the range of investigated parameters.

2. Modeling of Flange - Joint

In this study we perform to create model the L-flange joints with high- strength bolts and analysis in three steps (Figure 5).

2.1. Step0 (Figure 5)

Firstly we examine the work of one bolt with consideration of L flange - joint separation. As a proposed model of Herbert Schmidt, using the FEM to analysis and collecting the data regarding the types of bolted flange – joint, compare the results with previous research of Petersen (3 collapse mechanism) and Seidel (4 ranges of relation between tensile force acting on the tubular body and axial force in bolt). Besides that we also create the exactly the same model with Herbert Schmidt's model and Seidel model, analysis by using this study's method to verify two results.

2.2. Step1

In Step1 we will examine the response of all the bolts at one flange-joint of wind turbine tower. Using FEM software to model a part of wind turbine which has flange joint with high-strength bolts (Figure 4 at Step1), identify the response of each bolts when they are put together in the tower – joint model. It includes the pre – tension of bolt, axial force in bolt, critical states of bolt and the separation of ring flange – joint. Comparing with the analysis result of flange- joint model (segment model). Besides that from the result we understand the variety stiffness of the flange joint at the time when the flange - joint began separating.

2.3. Step2

From the analytical results we can calculate the stiffness at each flange joint in whole wind turbine tower.

Understanding the stiffness of each part in whole tower allowed modeling the whole tower like Figure 4 at Step2 simply. Analyzing this model and compare with the analytical results of the tower without considered the effects flange joint, we can understand the reduction strength of wind turbine with flange joint. From this we can concrete the general formula to define, calculate the variety of flange – joint's stiffness without conducting the FEM analysis.

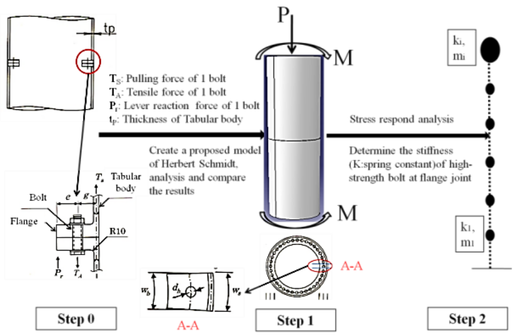

Figure 5. *The flowchart of the research*

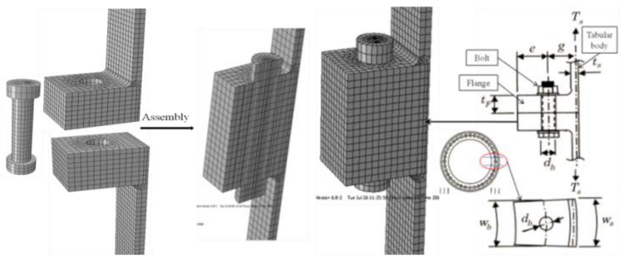

Figure 6. *The modeling apart L flange - joint with one bolt*

3. Results and Discussion

3.1. Step0

3.1.1. Model

In Step0 we model part of flange joint at one bolt like Figure 5 and the specifications of bolt and flange have been shown in Table 1. We create two part of L flange which have been joint by one bolt. In this analysis the bolt and flange were defined in solid type and homogeneous. The mesh was divided by element size (10 mm at each side of bolt, flange and tubular body, 5mm at hole of bolt), this model has about 6000 elements.

Table 1. *Specifications of bolt and flange joint*

Type of bolt	M36
Material of bolt	F10T
Effective cross-sectional area of bolt(Ab)	8.17cm^2
Distance between the end of flange bolt and center of bolt (e)	65 mm
Distance between center of plate of tubular body and center of bolt (g)	59 mm
Thickness of flange plate (tF)	75mm
Thickness of tubular body (ts)	18 mm
Shaft diameter of bolt (ds)	36 mm
Diameter of the bolt hole (dh)	39 mm
Material of flange plate and tubular body	SM400
Yield point stress intensity of flange plate and tubular body	235 N/mm^2
Yield point stress intensity of bolts	900 N/mm^2
$W_b \simeq W_s$	100 mm

3.1.2. Analysis Methods

In Step0 we perform to analysis in 2 periods. Period 1, we set up the pre-stress (pre-tensile force) into bolt until reaching to the initial axial force by using couple temp – displacement analytical method. It means we cannot set up pre-stress in bolt normally, so we must assume that the bolt has been cooled at the suitable temperature. Because the nuts at both ends of the bolts have been attached in the flange, therefore when the bolt is cooled, the bolts will automatically be set up the pre-stress. By the test gradually we can cooled the bolts until reaching to the initial axial force in bolt. In this study the initial axial force of bolt was calculated by this formula $T_V = 0.75 \times \sigma_y \times A_e = 675$ kN. In period 2, keeping the initial axial forces in bolts and the tubular body was pulled by tensile forces Ts. Besides that one important thing is interactions between the surfaces which contact each other (the bottom surface of above flange and the bottom surface of under flange, the surface of nut and top surface of each flange, axial curved surface of bolt and curved surface inside bolt hole). This interactions are defined by tangential behavior with friction formulation is penalty (friction coefficient is around 0.78).

3.1.3. Results

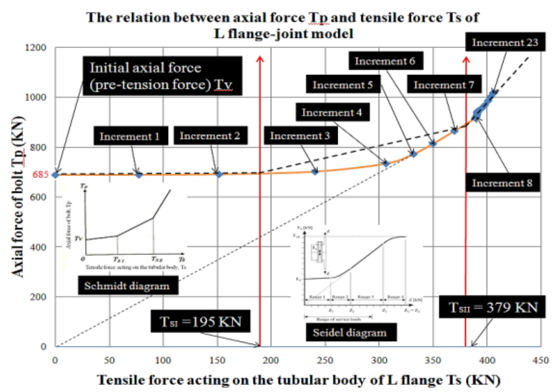

Figure 7. *The relation between axial force Tp and Tensile force Ts*

With FEM analysis results we have the relation between axial force in bolt and tensile force acting on the tubular body was shown in Figure 7. From this results and compare with the Schmidt-Neuper diagram and Seidel diagram (Figure 1, 4) they have the same curve. See the Figure 7 in the first step of analysis we put the initial tensile force (pre-tension) in bolt to Tv = 685 KN by Couple temperature – displacement method, the second step started after reaching to the initial tensile force on bolt by putting the pull force (tensile force). In the first period although the tensile force increased fast, axial force in bolt increased very slowly. This means that the pull force (tensile force) acting on the top of the flange was consumed to overcome the initial pressure force in the bolt.

Now we find the similarities between FEM analysis result with S – N diagram, collapse mechanisms was proposed by Petersen, and 4 ranges collapse mechanism was developed by Seidel.

With the configuration of this study was given (Table 1) we calculated the T_{SI} = 195 KN and T_{SII} = 379 KN. See Figure 7 the tri-linear was proposed by Schmidt has a good agreement with FEM analysis.

4 ranges was developed by Seidel:

Range 1(A): 0-Z1

The same with the collapse mechanism 1 of Petersen, the range 1 includes increments from 0 to 2. See Figure 7, 8 the Ts increased fast but the Tp almost approximated. The relationship curve between tensile force acting on tubular body and the axial force in bolt is linear curve. Stresses between flanges are reduced while contact zone is closed (Figure 8). The FEM analysis is suitable with this range.

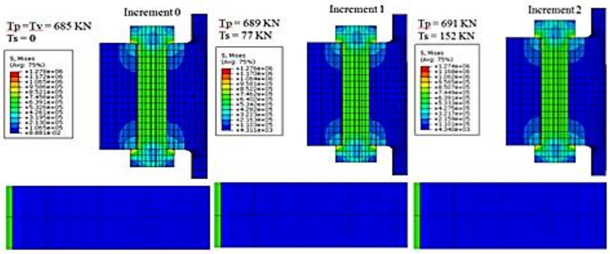

Figure 8. *Stress in bolt, flange, tubular body and the separation of flange joint at increment 0, 1, 2*

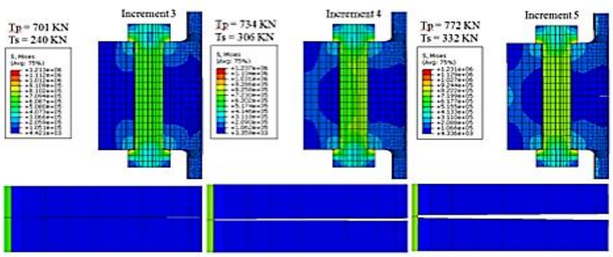

Figure 9. *Stress in bolt, flange, tubular body and the separation of flange joint at increment 3, 4, 5*

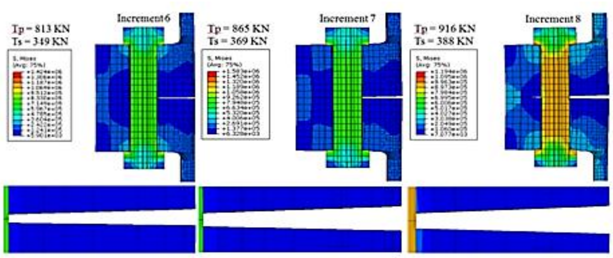

Figure 10. *Stress in bolt, flange, tubular body and the separation of flange joint at increment 6, 7, 8*

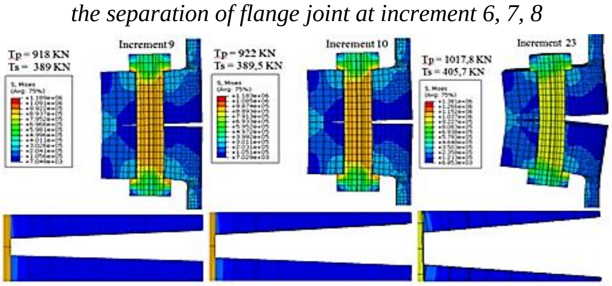

Figure 11. *Stress in bolt, flange, tubular body and the separation of flange joint at increment 9, 10, 23*

Range 2(B): Z1-Z2

The range 2 includes increments from 3 to 5 (Figure 7). See the Figure 7, 9 the relationship curve between tensile force acting on tubular body Ts and axial force in bolt Tp is nonlinear curve. Successive opening of flanges. This range is suitable with FEM analysis.

Range 3(C): Z2-Z3

This range includes the increment from 5 to 8. See the Figure 7, 10 the relationship between Tp and Ts is linear and when connecting increment points from 5 to 8 and coordinate origin, all point make a line like dash line in Figure 7. It means that open connection with slope depending on loads geometry. The range 3 also has a good agreement with FEM analysis.

From the increment 7 to 8 the tensile acting on tubular body reached to T_{SII} = 379 KN.

Range 4(D): From Z3 to onward

This ranges includes increment from 8 to onward. See Figure 7, 11. Plastification of bolts and/or flange until failure of the connections.

Figure 12 makes more clearly that from the increment 2 to increment 3 the connection started separated (Ts = T_{SI} = 195 KN).

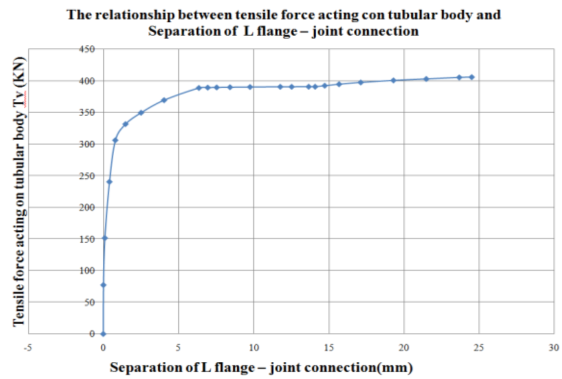

Figure 12. *The relationship between tensile force Tv and Separation of flange connection*

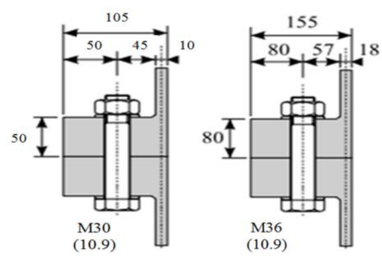

Figure 13. *The configuration of Schmidt – Neuper test's model (left) and Seidel test's model*

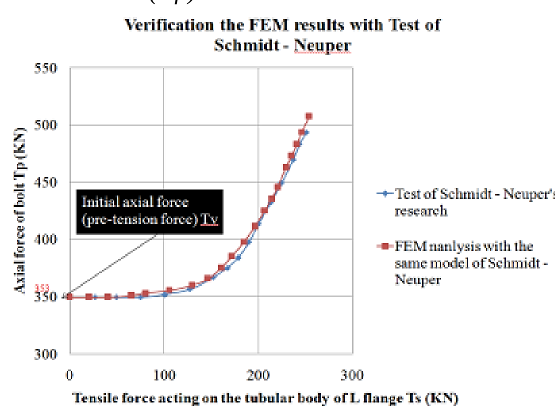

Figure 14. *The verification FEM analysis with Schmidt – Neuper test*

To verify the FEM analysis results we compared with the test results which were done by Schmidt – Neuper and Seidel (Figure 13).

With the same analysis method of this study, we have the results as Figure 14, 15. From this the FEM analysis result and the test result of Schmidt – Neuper and Seidel have good agreement. These results proved that the FEM analysis method and the results of this study have been verified.

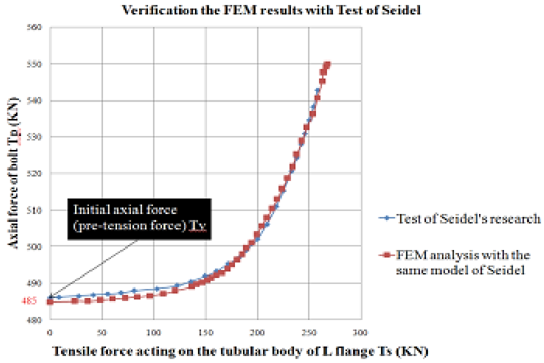

Figure 15. *The verification FEM analysis with Seidel test*

3.2. Step1

3.2.1. Model

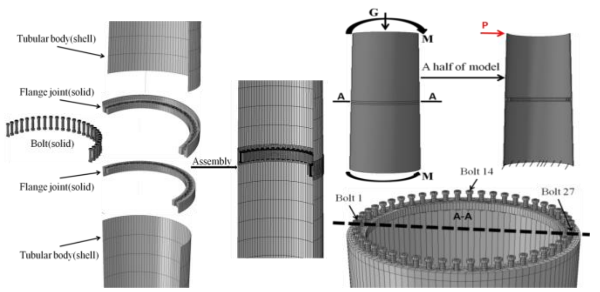

Figure 16. *The modeling a half of flange joint in wind turbine tower*

In Step 1 we create model is a part of tower at the flange joint like Figure 16. Because this part of model is very big when compare with the size of one bolt so we diverged into three part. Two tubular bodies are defined by shell, two flange joint are defined by solid and 52 bolts are defined by solid. The number elements of the half of this model are about 100000 elements. The bolts were numbered from 1 to 27 and the middle bolt is bolt 14.

Table 2. *Specifications of bolt and flange joint*

Outer diameter of tubular body Dp	1675	
Inner diameter of tubular body Dpi	1639	
Inner diameter of flange F	1409	
Diameter of bolts circle G	1539	
Number of bolts (in a half of flang joint model)	26 + 2×a half of bolt	
Thickness of flange plate (tF)	75mm	

3.2.2. Analysis Methods

The same analysis method with step 0, we also set up the pre-stress into bolts until reaching to the initial axial force by using couple temp – displacement analytical method. In the other hand, because this model is very big so reducing the analysis's time only the half of this model was created and analysis (this model is symmetric and the symmetric axis is A-A in Figure 16. Besides that in this model there are 2 types of sections (solid and shell). Therefore the constraint between tubular body (shell) and flange joint (solid) was defined by shell to solid coupling. A shell-to-solid coupling constraint allows coupling the motion of a shell edge to the motion of an adjacent solid face. For each shell node involved in the coupling, a distinct internal distributing coupling constraint is created with the shell node acting as the reference node and the associated solid nodes acting as the coupling nodes. Each internal constraint distributes the forces and moments acting at its shell node as forces acting on the related set of coupling surface nodes in a self-equilibrating manner. The resulting line of constraints enforces the shell-to-solid coupling. When cutting a part of tower at flange joint to analysis, we must put the reaction force at the cutting places (moment M, self weight). To simplify the analysis we change the forces diagram acting on the flange joint of tower. Fixing the below tubular body and putting the horizontal force at the top of above tubular body like Figure 16.

3.2.3. Results

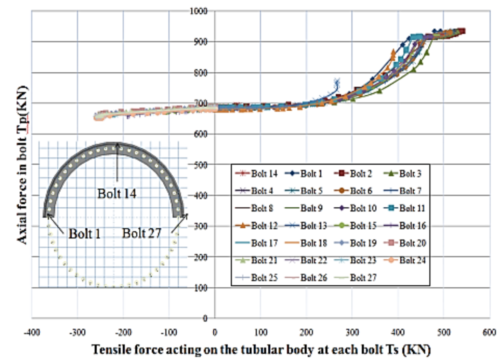

Figure 17. *The relation between axial force and tensile force acting on the tubular body of each bolt*

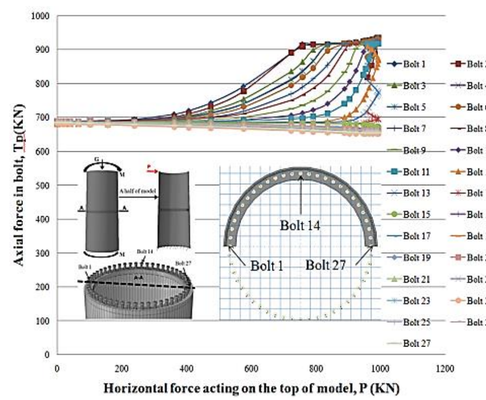

Figure 18. *The relation between axial force and horizontal force acting on the top of model*

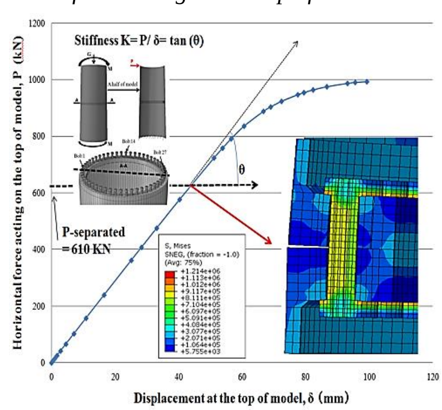

Figure 19. *The relation between horizontal force and displacement at the top of model*

The relation between axial force and tensile force acting on the tubular body of each bolt (from bolt 1 to bolts 27 were defined like Figure 16) was shown in Figure 17. From the bolt 1 to bolt 13, the shape of the analysis's results are the same with step 1. It means that the model and analysis method in this step is fine. Besides that, from bolt 1 to bolt 13 the bolt are pulled because the tubular body and flange joint from bolt 1 to bolt 13 was pulled and the opposite side, from the bolt 14 to bolt 27, the initial axial forces in each bolt are almost unchanged. It means that the tubular body and flange joint are compressed. In Figure 18 it expressed the relation between axial force and tensile force acting on the tubular body of each bolt. We see that when the horizontal force increase the axial force in bolt also increase but it is very slowly in the first, the increasing are descending from bolt 1 to bolt 13. From bolt 14 to bolt 27 the axial force are almost unchanged with the initial axial forces. In Figure 19 we can find out the relation between horizontal force and displacement at the top of model. The relationship between horizontal force acting on the top of model and displacement at the top of model was shown in Figure 19. The analysis results show that when the horizontal force increased from 0 to 610 KN, horizontal force and displacement have linear relation. It means that the stiffness of tower in this range of loading was not changed. From horizontal force P = 610 KN the relation was nonlinear. If call K = P/**δ** is the stiffness of tower, from Figure 19 can see that K decreased. Besides that from FEA results at horizontal force at the top of model reached to P = 610 KN the ring flange connection started separated. From now we call P = 610 KN is P- separated.

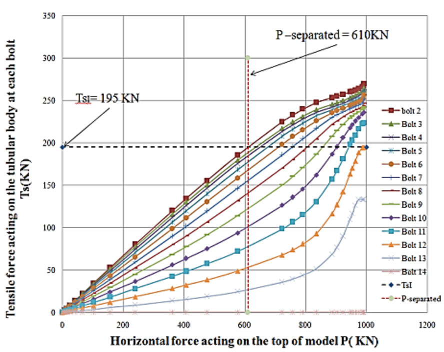

Figure 20. *The relationship between horizontal force acting on the top of model, P and tensile force acting on the tubular body at each bolt*

Figure 20 showed the relationship between horizontal force acting on the top of model, P and the tensile force acting on the tubular body at each bolt. At previous step mentioned that the T_{SI} = 195 KN can be calculated by using Schmidt – Neuper formula. According to the results in previous step at tensile force acting on the tubular body of each bolt Ts reached to T_{SI} = 195KN like Schmidt – Neuper tri- linear diagram, the L flange – joint started separated (the stiffness of l flange – joint reduced). Here, see the Figure 20, at the time bolt 1 reached to the T_{SI} = 195 KN (it mean that the stiffness of part L flange – joint at bolt 1 reduced), the horizontal force acting on the top at model also reached to the P- separated = 610 KN. Compare with the Figure 19, this phenomenal was suitable with the time when the stiffness of tower – joint was also reduced and the ring flange – joint started separated.

4. Conclusions

+ With FEM analysis the L flange – joint, model of tower – joint were reproduced like the real worked mechanism

+ The FEA results have a good agreement with tri-linear diagram (S-N diagram), 3 collapse mechanisms of Petersen and new 4 ranges failure mode Seidel

+ With S-N formula, T_{SI}, T_{SII} were calculated. From the results we can find out that when the tensile force acting on the tubular body Ts=T_{SI}, the L flange – joint started separated (the stiffness of L flange- joint reduced)

+ The comparison FEM analysis result with Schmidt – Neuper's test result and Seidel's test result have good agreement. The FEA results have been validity

+ Horizontal force P >P-separated (the stiffness of tower – joint decreased). At P –separated the ring flange stared separated and matched with the time when the tensile force acting on tubular body T_S reached to T_{SI}

+ Proceeding: With the results got from the FEM analysis, and S-N formula we try to concrete the general formula to modify the variety stiffness of flange – joint and evaluate the not only the variation of the stiffness but also the reducing of the proof-strength of tower during the operation.

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(The Board of Editors received the paper on 25/10/2014, its review was completed on 10/12/2014)