Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 22
ISSUE 1
May
2007

FEM modelling of fatigue loaded bolted flange joints

T. Smolnicki, E. Rusiński*, J. Karliński
Institute of Machines Design and Operation, Wroclaw University of Technology, ul. Lukasiewicza 7/9, 50-371 Wroclaw, Poland
* Corresponding author: E-mail address: eugeniusz.rusinski@pwr.wroc.pl

Received 02.04.2007; published in revised form 01.05.2007

Analysis and modelling

ABSTRACT

Purpose: The main purpose of this paper is to describe the modelling of large flexible objects in which bolted joints are used and also to present a new FEM calculation methodology of these objects.
Design/methodology/approach: In bolted flange joints of flexible constructional elements, bolts are subject not only to tension and torsion but also to bending. Identification of straining of each bolt is only possible by means of numerical methods e.g. the finite element method FEM. In case of large objects, the calculation problem is faithful projection of the phenomena taking place in direct zone of the contact of screw-nut pair. The application of global equivalent models of the whole joint is necessary, to make it possible to precisely determine internal loads in individual bolts and then local models to determine stress fields necessary to assign durability. Calculation methodology based on the construction of two coherent models has been described: global - of an entire flange joint, and local - of a single bolt joint.
Findings: The elaborated methodology was applied to estimate the flange joint in the heat exchanger with rotating heating surfaces that was subject to damage. The causes of damage of flange joint were found.
Practical implications: Used methodology of FEM modelling of bolted flange joints based on two coherent models may be applied for different similar objects. The paper provides detailed description of methodology steps.
Originality/value: The described methodology may be successfully applied to the analysis of large objects, however, significant geometric features with dimensions small in relation to dimensions of the whole object. Thanks to the application of two coherent models, it is possible to reflect all essential phenomena in the FEM model, both in the global scale - of the entire object, and local – a significant fragment of the joint.
Keywords: CAD/CAM; FEM; Flange joints

1. Introduction

Most commonly bolted flange joints find application in hydraulic systems for joining individual elements. Their basic task is assurance of the tightness of connection [1,2,3,4]. Another area of application is joining elements of machinery and devices. In that case the essential task of the connection is transfer of own loads and technological loads between elements [5].

When thin-walled elements with high flexibility are joined and subject to complex, changing in time loads, traditional calculation methods relying on simple multiplication of carrying capacity of single bolt joint are not adequate and either lead to over dimensioning of design, or create a threat of destroying the joint, which could cause the threat of operators' life and serious economic losses.

The bolted flange joint (Fig. 1.) is commonly applied to connect structural elements of machinery and devices. The larger the joint diameter, the stronger the impact of flexural flexibility and flexibility of joined elements [6]. This influence is significant especially in case of connections of rotating elements like drive shafts, rotors, large-diameter antifriction bearings [5] and so on, because the connection is being subject to alternate bending. The precise verification on the criterion of durability requires high accuracy in determining the stress fields [7]. The most strenuous joint elements are bolts with usually high strength class. Bolts, apart from the load of preliminary tension (clamping force) and torsion (if hydraulic or electric torque wrench is not applied), are subject to extra stretching or relieving, and bending (Fig. 1.) [8].

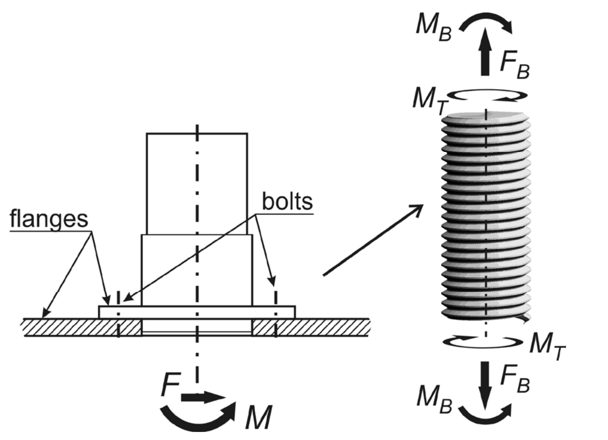

Fig. 1. Example of bolted flange joint loaded with transverse force F and bending moment M and schema of loads of the bolt: tensioned with axial force F_B, twisted with moment M_T and bent with bending moment M_B

Classical calculation methods make it only possible to take into account the bolt axial stresses and tangent stresses from shearing produced by torsion. The impact from flexural flexibility of flanges and the impact from radial clearances are not included. In order to determine the effort (strain) of joint elements reliably, the application of numerical methods is necessary [9,10], e.g. finite element method FEM [11,12,13].

2. Methodology description

The basic calculation problem in bolted flange joints is the identification of phenomena occurring in the bolt joint zone of the thread and between the head of the bolt and the flange. When finite element method is applied, the assurance of suitable quality of finite elements mesh is necessary in this zone. The zones for each of the bolts of the joint have small dimensions considering the size of the whole object. The basic contradiction results from it: either the calculation of the whole object is possible, but the correct reflection of the zone of thread is impossible, or we analyse exactly the single bolt joint, without taking complex impact of flexibility of the object into consideration.

The solution to the above-mentioned problem may depend on insertion of equivalent models of bolt joint strictly reflecting the rigidity of the joint. On the block diagram (Fig. 3.) the accepted procedure based on the application of coherent models – global, of the entire flange joint and local, of a single bolt joint is presented.

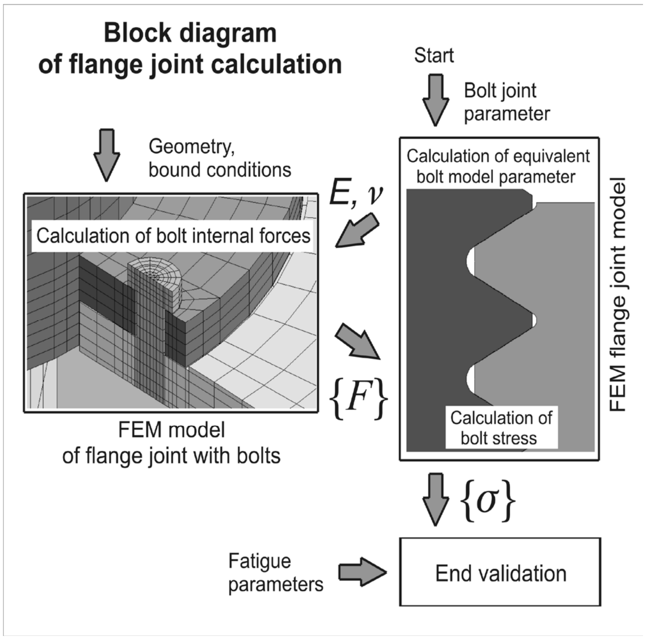

Fig. 2. Block diagram of flange joint calculation

The calculation is carried out in five Steps (Fig. 2.):

- Step 1. The detailed FEM model of the single bolt joint is built, completely reflecting geometry of the bolt and fragment of the flange. Contact interactions between elements are taken into consideration in the model, the friction on the thread and the elastic-plastic model of the material included. Rigidities of the joint for elementary loads are determined (Fig. 1.): tension by axial force F, torsion M_T and bending M_B, for bolt loaded with clamping force.
- Step 2. Parameters of the equivalent bolt joint model are defined, based on the results obtained (Fig. 3.). In that model in place of the thread an equivalent anisotropic layer of material is introduced. Modules for the material of the layer E_r, E_θ and E_z are calculated based on the rigidity determined in Step 1.
- Step 3. The global model of the flange joint is built with equivalent elements (Fig. 3.). Contact phenomena [14] and clamping force of the bolt joint are taken into consideration. Generalized sectional forces are assigned for individual bolts {F}, for representative sets of loads.
- Step 4. Generalized extreme sectional forces $\{F\}_{max}$ and $\{F\}_{min}$ are applied to the detailed model. Fields of stresses in the bolt joint are obtained from the performed calculations. Tensors are determined: average stress $\{\sigma_m\}$, stress amplitude $\{\sigma_a\}$ and stress range $\{\Delta\sigma\}$. Equivalent values: σ_m, σ_a and $\Delta\sigma$ are calculated according to the Huber - von Mises hypothesis.
- Step 5. Final estimate of the flange joint. Fatigue analysis is carried out based on the previously determined values with numerical or classical methods.

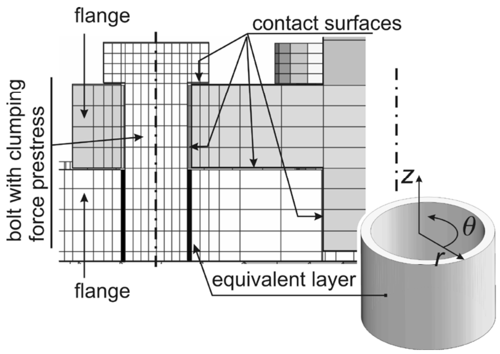

Fig. 3. Basic phenomena taken into consideration in global model of the flange joint. Equivalent layer of finite elements reflecting rigidity of the bolt joint

3. Results

The elaborated algorithms of the procedure were applied to the estimate of reasons for damage to the flange joint in the heat exchangers with rotating heating surfaces of a fluidal power boiler. The connection was made with 8 pieces of M42 bolts with strength class 8.8. The surfaces of destruction on individual bolts had the fatigue character, and the form of destruction (Fig. 4.) attested about bending the bolt [15,16].

A detailed model based on the higher row elements was constructed (Fig. 5.). The parameters of the equivalent model were determined based on the calculations performed. Then the global model was constructed (Fig. 6.).

Fig. 4. Destroyed M42 bolt from flange joint

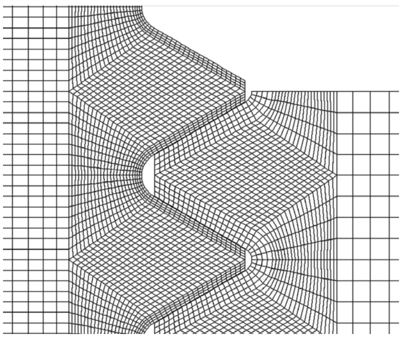

Fig. 5. Fragment of the mesh on the detailed model

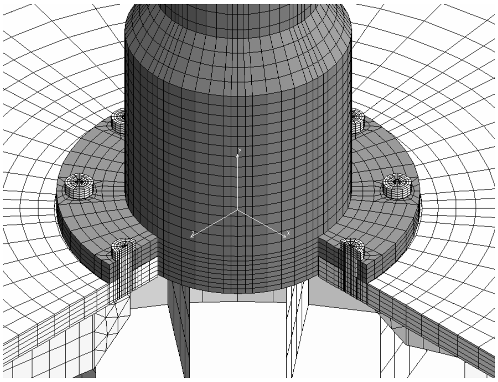

Fig. 6. Global model of the flange joint – section view

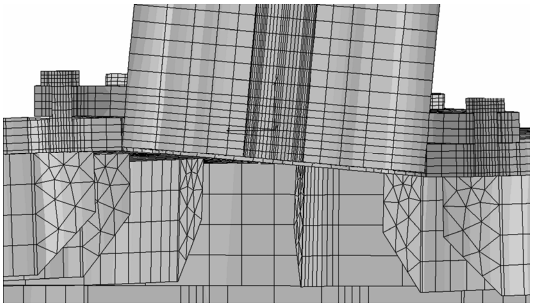

Fig. 7. Form of deformation (100:1 scale)

Form of global model deformation and stress contour line in the bolt are shown in Figures 7 and 8.

Appointed generalized sectional forces were applied as input data for repeated calculations on the detailed model. In Figure 9. the obtained contour lines of equivalent average stresses and amplitudes of stresses are shown.

The obtained results served for the fatigue analysis conducted in space (σ_m, σ_a). Exemplary results for clamping force M_{nap} equal to 1000Nm and coefficient of friction on the thread μ=0.08 are shown in Figure 10, where the contour lines of safety factor in relation to boundary line on the Soderberg diagram are shown. Value 1 means the position of the point of work on the Soderberg line, values below 1 mean the line is exceeded.

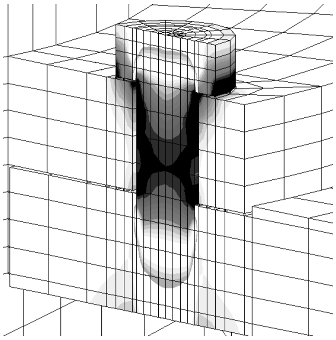

Fig. 8. Stress contour line in the bolt

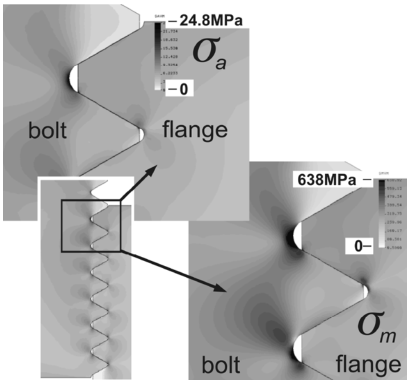

Fig. 9. Contour lines of equivalent average stresses σ_m and contour lines of equivalent stress amplitudes σ_a

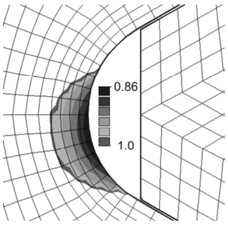

Fig. 10. Safety factors assigned numerically

4. Conclusions

The methodology presented can be successfully applied to the analysis of large dimension objects, possessing, however, significant geometric features with dimensions small in relation to dimensions of the whole object, e.g. to flange joints. Thanks to the application of two coherent models, it is possible to reflect in the FEM model all essential phenomena, both in the global scale - of the entire object, and local – a significant fragment of the joint.

The answer to the question was obtained in the analytical example brought up for the reason of damage to a responsible constructional joint in heat exchangers with rotating heating surfaces in a fluidal power boiler. The reason for damage lied in the application of bolts with high rigidity tightened with too much force, instead of flexible bolts.

References

[1] T. Takaki, T. Fukuoka, Finite element analyses of bolt-up operations for pipe flange connections, ASME Pressure Vessels and Piping Conference 416 (2001) 141-147.

[2] K. Jeong, J.C. Yoon, B.S. Kang, Finite element analysis and modelling of structure with bolted joints, Applied Mathematical Modelling 31/5 (2007) 895-911.

[3] M. B. Marshall, R. Lewis, R. S. Dwyer-Joyce, Characterisation of contact pressure distribution in bolted joints, Strain 42/1 (2006) 31-43.

[4] K. Urbonas, A. Daniunas, Behaviour of semi-rigid steel beam-to-beam joints under bending and axial forces, Journal of Constructional Steel Research 62/12 (2006) 1244-1249.

[5] T. Smolnicki, Physical aspects of coherence of large-size slewing bearings and deformable supporting structures, Wroclaw University of Technology Press, Wroclaw 2002 (in Polish).

[6] G.L. Xiong, H. Chen, J.M. Yi, Instability mechanism of a rotating disc subjected to various transverse interactive forces, Journal of Materials Processing Technology 129/1 (2002) 534-538.

[7] Y. Li, New research on the stress field of elastic-plastic small deformation problems, Journal of Materials Processing Technology 138/1 (2003) 508-512.

[8] D. Lehmann, Nonlinar axis force and bending moment distribution in bolt clamped L-flange, Stahlbau 9 (2003) 653-663 (in German).

[9] S. Troup, R.Y Xiao., S.S.J. Moy, Numerical modelling of bolted steel connections, Journal of Constructional Steel Research 46/1 (1998) 269-269.

[10] A. Nechache, A.H. Bouzid, Creep analysis of bolted flange joints, International Journal of Pressure Vessels and Piping 84/3 (2007) 185-194.

[11] E. Rusiński, J. Czmochowski, T. Smolnicki, Advanced finite element method for load-carrying structures of machines, Wroclaw University of Technology Press, Wroclaw 2000 (in Polish).

[12] A. Dombrowski, FEM calculation clamped flange joints. Interner Bericht WE 60/96. Germanischen Lloyd Hamburg, 1996 (in German).

[13] A.M. Harte, D.Mc Cann, Finite element modelling of the semi-rigid behaviour of pultruded FRP connections, Journal of Materials Processing Technology 119/1-3 (2001) 98-103.

[14] D. Siminiati, FEM numerical algorithm on contact problem for non-conform elastic bodies, Proceedings of the 11th Scientific International Conference "Achievements in Mechanical and Materials Engineering" AMME'2002, Gliwice - Zakopane, 2002, 495-498.

[15] H. Razavi, A. Abolmaali, M. Ghassemieh, Invisible elastic bolt model concept for finite element analysis of bolted connections, Journal of Constructional Steel Research 63/5 (2007) 647-657.

[16] X. Feng, L. Zhongqin, L. Shuhui, X. Weili, Study on the influences of geometrical parameters on the formability of stretch curved flanging by numerical simulation, Journal of Materials Processing Technology 145/1 (2004) 93-98.