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Calculation of Bolted Flange Connections

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TRACT

In Europe, in 2001 the new standard EN 1591 for strength and tightness proofs of bolted flange connections (BFC) of floating type flanges was released. In addition, the German nuclear code was revised regarding the calculation of BFC. With this standard not only the floating type but also the metal-to-metal contact type of flanges (MMC) can be treated. Additionally, the ASME code is the basis for the flange calculation in the European standard EN 13445, which is the standard for unfired pressure vessels.

In compliance with the goal of the calculation, the different calculation codes can be used. There must be a differentiation between the design of the components, the determination of the prestress values for assembly, the stress analysis and the tightness proof of the BFC.

In this paper, all parameters which influence the function of the bolted flange connection are considered. Also, the range of use of the different standards and the calculation algorithm are discussed.

KEY WORDS: flanges, bolted flange connections, flanged joints, gasket factors, gasket characteristics, calculation, design, tightness proof, stress analysis, assembly.

INTRODUCTION

The demands on BFC which are given by the operational conditions determine the design of the BFC. Basically, there are two different designs available, the gasket floating between the pair of flanges and the meat-to-metal contact type, see **figure 1**. These two types do not differ only in their geometrical design, but also the function of the two types is completely different. For a realistic analysis of the two designs different calculation algorithms and different gasket factors are required.

In a floating type of BFC, all loads affect the gasket stress. The bolt load in assembly implies directly a gasket load, if external forces and moments are neglected in a first step. All load changes in services, like increasing or decreasing temperature of the components, internal pressure or external forces and moments, result in gasket stress changes. The gasket stress increases or decreases through these loads. The reaction of the connection depends on the stiffness and on the material characteristics of the components.

In metal-to-metal contact type of flanges, the gasket is deformed in assembly until the contact of the flanges is reached. The gasket may be put in a groove or metallic rings prevent an additional deformation, the metal-to-metal contact situation is defined exactly. Increasing the bolt load after MMC is reached does not effect the behavior of the gasket anymore. The tightness of the connection cannot be improved by increasing the bolt load, the gasket stress and therefore the reachable tightness class is fixed when the MMC is reached. A higher bolt load than the one required for reaching MMC shall guarantee, that the MMC is not lost in service conditions.

This effect shows the main difference between the two different designs, the tightness behavior of the two types of BFC. In assembly, the leakage channels through the sealing element and between the sealing element and the flange surfaces must be closed. While the maximum gasket stress for the MMC type is limited by the design, an increase of the bolt load improves the tightness of the floating type of flanges. If the required tightness class is not achieved in the MMC situation, the gasket stress cannot be increased anymore to get lower leak rates.

On the other side, if the gasket stress is high enough in the MMC situation, the tightness class will be kept as long as the MMC is not lost. Only relaxation effects of the gasket material could cause an increase of the leak rate, all loads which occur in service on the BFC have no influence on the tightness behavior.

In the floating type the gasket stress can be increased during assembly to improve the tightness behavior. A disadvantage of this design is of course, that all load changes in service affect the function of the gasket. If the unloading of the gasket is not permissible anymore, a leak may occur.

Figure 2 shows the differences between the floating type and the MMC type of BFC.

For a correct function of a BFC, that means to guarantee tightness (achieve the demanded tightness class) and to prevent destruction of one of the parts (flanges, bolts, gasket), it is necessary to take the following parameters into account, **figure 3**:

- The type of medium and the relevant loads (internal pressure, temperature, temperature changes, additional forces and moments etc.) must be known.
- A correct choice of the components (flanges, bolts, gasket) is necessary for the relevant loads; additionally the material characteristics (especially the gasket factors) must be provided.
- The prestress value for the bolts have to be determined and the stress analysis and the tightness analysis has to be performed.
- Last but not least, the prestress accuracy must match the demands.

These boundary conditions for the correct function of a flange connection must be considered in an as detailed as possible calculation. This calculation can have various goals depending on the requests. In some cases, only the design of the single components is carried out, in fact without an detailed analysis of the complete system. Also tightness and strength proofs of the flange connection are carried out under consideration of all influence parameters called above, however. The general procedure of a flange calculation is shown in **figure 4**.

The contribution shall light the state of the art after introduction of the European standard EN 1591 and the revision of the German nuclear code KTA 3211.2 with regard to the flange calculation critically and point out the advantages but also the required interpretations of these sets of rules to the user.

CALCULATION PARAMETERS

The most essential parameters of the flange calculation represent the loads, the construction of the single components and the material choice.

The medium has primarily to be counted to the loads since this has an influence on the resistance of the flanges and the gasket. The gasket tightness characteristics as well are influenced by the medium. The internal pressure, the temperature of the components, if necessary temperature changes, temperature distributions and also additional forces and moments play a role in the operation states besides the medium.

They are on the one hand decisively for the choice of the construction including the gasket type, on the other hand they are required for the calculation, for a tightness (limitation of the leak rate to the required tightness class) and for strength proof (failure of the connection) inevitably.

Sufficient knowledge about the relevant load cases therefore is a central point for the flange calculation. Unfortunately, the appearing loads aren't always known, what absolutely can lead to a faulty determination of the required prestress values. In critical cases, therefore the loads have to be determined in additional measures like pipe calculation or measuring.

In principle, at the analysis of a flange connection concerning the construction and the material choice you must distinguish, whether it is an existing connection or whether a connection shall be designed newly.

At existing connections constructive changes are frequently connected to high costs, so that the geometries and the used materials of both the flanges and the bolts are given here as fixed sizes. The gasket can merely be selected and exchanged, if necessary, according to the operation conditional requests in simple way.

At flange connections to be designed newly the connection's both suitable flanges and bolts (type, design, material), and suitable gaskets (type, design, gasket characteristics), can be selected after the fundamental specification of the type of the connection.

Besides the correct choice of the geometry forms of the components, which is made easier by numerous standards, the choice of the flange and bolt material is an important role. The material determines namely not only the highest permitted bolt load, it also determines the mechanical behavior of the complete system. By unfavorable material combinations with very various thermal expansion coefficient additional strengths can be caused by temperature changes, which can lead to inadmissible stresses in a component or which can cause a decreasing of the gasket stress under the required gasket stress and cause a leakage therefore.

At the choice of the sealing element the required gasket type is of first interest. Whether the gasket is floating between the flanges or whether the flanges are in metal-to-metal contact has to be decided here. For the gasket type selected "correctly", first details on the long time behavior are required. This concerns the resistance against the medium to be sealed up, the change of the tightness behavior and the corrosion behavior at given flange material and medium.

For the choice of the gasket used in a floating type as well as for the required calculation of the connection, the gasket characteristics according DIN 28090-1 or prEN 13555 are relevant, also see **figure 5**:

- minimum required gasket stress for a given tightness class L in assembly $\sigma_{VU/L}$ ($Q_{MIN(L)}$),
- minimum required gasket stress for a given tightness class L in service $\sigma_{BU/L}$ ($Q_{SMIN(L)}$),
- maximum allowable gasket stress in assembly σ_{VO} ($Q_{SMAX}(RT)$) and in service σ_{BO} ($Q_{SMAX}(T)$),
- modulus of elasticity E_D (E_0 and K_I) and
- deformation of the gasket in the relaxation test Δh_D (creep relaxation factor g_C).

Because of the completely different function, for the MMC type of flanges different gasket characteristics are necessary. These factors, which are not standardized yet, are:

- gasket stress to reach the MMC σ_{MMC},
- maximum allowable internal pressure $p_{MMC/L}$ for a given tightness class L and
- creep relaxation factor g_{MMC}.

With these gasket factors there are material characteristics for the flange calculation at the disposal, which can be seen on one hand in analogy to strength values of the flange and bolt material and which describe on the other hand the tightness behavior of the sealing element. With these gasket factors both, strength and tightness proofs can be done.

CALCULATION

In the course of the harmonization of the European standards also the flange calculation methods have been regarded. The calculation algorithms used in the European standard are the proceedings to "Wölfel" (EN 1591) and to "Taylor-Forge" (EN 13445). For the German users in the nuclear sector the specifications in the KTA rules (particularly KTA 3201.2 and 3211.2) must be taken into account. All these calculation methods apply to connections at which the gasket is floating between the flanges.

At present special proof methods for MMC type flanges will be released soon (KTA 3211.2). There is no other calculation code available which treats MMC.

Detailed individual calculations are possibly using finite elements method on linear elastic or elasto-plastic base, for e.g. for the determination of local stress distributions for fatigue analysis. With elasto-plastic analysis the gasket behavior can be modeled adequately, if necessary.

However, these FEM calculations subsequently shall not be considered. In the following the different analytical calculation proceedings are discussed with regard to

- design,
- tightness proof and
- strength proof.

DESIGN

In Germany, the DIN E/V 2505 (1964, 72, 86, 90 /10/) stood for the design of flange connections to the disposal. This calculation standard was in principle the basis for the AD-Merkblatt and the KTA rules.

In the design of a flange connection the internal pressure, the prestress value, external forces and moments as well as real gasket characteristics are taken into account as calculation parameter. However, it doesn't become a detailed analysis of the complete system. With simple considerations required forces get calculated for every service condition, as well the maximum allowable forces are calculated. This applies both to the bolts and to the gasket. The flanges are treated over the resistance moments.

Because of uncertainties or insufficient knowledge about the existing boundary conditions construction surcharges or higher safety coefficients are used.

For MMC the check of the sufficient dimension of the flanges consists of the ensurance of an adequate stiffness and therefore of a restricted flange rotation.

Worldwide mostly used for the design of BFC is the ASME standard, which also has had influence on the national standards of some European countries. As calculation parameter the internal pressure and the external forces and moments can be taken into account. The behavior of gasket is feigned with very formal gasket factors (m and y). Changes of the forces between assembly and operation cannot be calculated. Class designed flanges became calculated according to ASME.

The calculation method to ASME based on the basis of the elasticity theory leads to flanges with high stiffness. Last but not least, this is the reason why the ASME procedure was included into the pressure vessel standard EN 13445.

TIGHTNESS PROOF

For a tightness proof the choice of calculation methods is a little restricted. The ASME code is a pure strength proof since the tightness characteristics of the gasket aren't taken into account sufficiently. The EN 1591 and the KTA 3201.2/KTA 3211.2 therefore stand for the execution of a tightness proof to the disposal.

The requirements on the tightness of the BFC are treated in the gasket characteristics, which are given in dependence on the tightness class.

Under consideration of the geometries and materials first the stiffness of the singles components is calculated, the real loads like internal pressure, additional forces or thermal expansions are taken into account as well as relaxation effects, and the resulting bolts and gasket strengths can therefore be calculated under consideration of the force and deformation balance for every following operation condition from the assembly condition.

The resulting gasket stress arises from the gasket forces in every operating state. The check of the retention of the required gasket stress which is in dependence on the initial gasket stress in assembly leads to the tightness proof.

For MMC the tightness proof is carried out via the proof of the retention of the MMC situation. The tightness class which was reached at the assembly in the metal-to-metal contact state, will be valid as long as the MMC isn't lost. It is therefore sufficient to furnish the proof that the two flange don't loose contact. To this the balance of forces and deformations are also taken into account.

STRENGTH PROOF

In the calculation method to ASME the prestress is related to the maximum allowable bolt stress and not to required bolt forces for achieving the demanded tightness class while the permitted bolt stress in service is restricted to relatively low values. A detailed proof of the complete connection under consideration of the stiffness of the components isn't carried out. However, the positive experience covers the applicability of this "pragmatic" procedure.

The calculation methods of the KTA are based on the "plastic load theory". In EN 1591 an elastic analysis of the load deformation relation between all components of the BFC is used for the tightness proof, for the strength proof load ratios are calculated which are based on limit load analysis calculation.

Allowable stresses (or safety factors) for flanges and bolts are defined in the KTA for the stress analysis in every operation step. The stresses actually appearing during the operation states in the BFC must be limited against these allowable stresses.

In this method which takes plastic deformations into account only global stresses are expelled as measure for the integrity of the BFC. The stresses are limited in single flange cross-sections, in the bolting and in the gasket cross-section.

The method to EN 1591 follows in the strength proof primarily of the flanges a different way. No allowable stresses are defined directly in EN 1591 for the flange and bolt materials, the nominal design stresses must be determined by the end-user according to other standards.

Another difference is that no single flange cross-section is treated. The strength proof of the flange is done with a fictitious resistance moment which is dependent on the geometry and material sizes of the flange ring and the shell. The user recognizes an overload of a cross-section from the calculation results of various variables, if these are interpreted correctly. In addition, no stresses are calculated, only the load ratio is given.

In EN 1591 the scattering of the tightening device is taken into account. While in the assembly condition for all components the maximum resulting forces caused by the scattering is treated for the stress analysis, in the following operational conditions only the minimum forces are treated. The stresses in the following conditions actually appearing are higher than these minimum stresses, but since these excessive stresses are secondary ("passive") stresses which disappear by plastic deformations, this is permitted.

For MMC the strength proof can be reduced on the limitation of the flange rotation and of the bolt load . By the demanded limitation of the flange rotation for the safe function of a MMC only negligibly small stresses are caused in the other cross-sections of the flange.

CONCLUSIONS

For floating type of BFC in the nuclear industry in Germany the rules of the KTA 3201.2/3211.2 are common practice. With the development of KTA 3211.2 a calculation method for MMC is available for the first time.

Within these calculation methods all relevant loads are taken into account. These calculation procedeures can be used both for the strength proof and for the tightness proof.

By the harmonization of the European calculation standards the EN 1591 will more strongly come into the focus of the flange calculation. Up to now, there are only a few experiences on the application of this standard available. Also, some modifications for a simplification for end-users are necessary.

A modification of the EN 1591 algorithm is necessary to simplify the calculation. This particularly concerns the creep relaxation factor and the dependence of the minimum required gasket stress on the initial gasket stress at assembly before.

As further development of the EN 1591 the MMC also shall be a calculation method built in the European standardizing committee.

The "pragmatic" ASME proceeding is taken into the European standard EN 13445. However, a detailed analysis of the BFC as this is required for a tightness and strength proof isn't carried out within the ASME method.

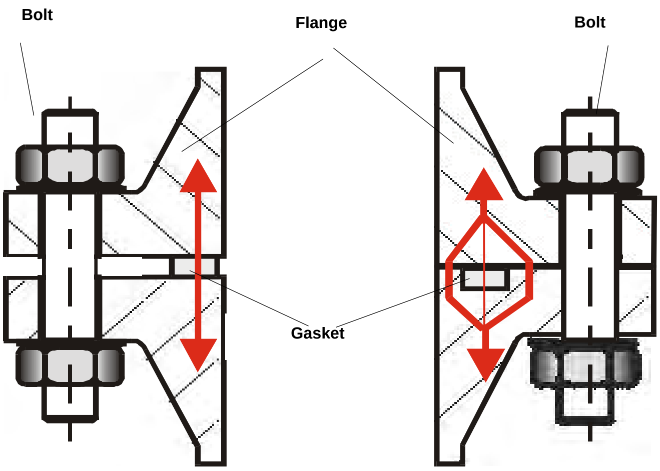


Fig. 1: Bolted flange connections of floating (left) and metal-to-metal contact type (right)

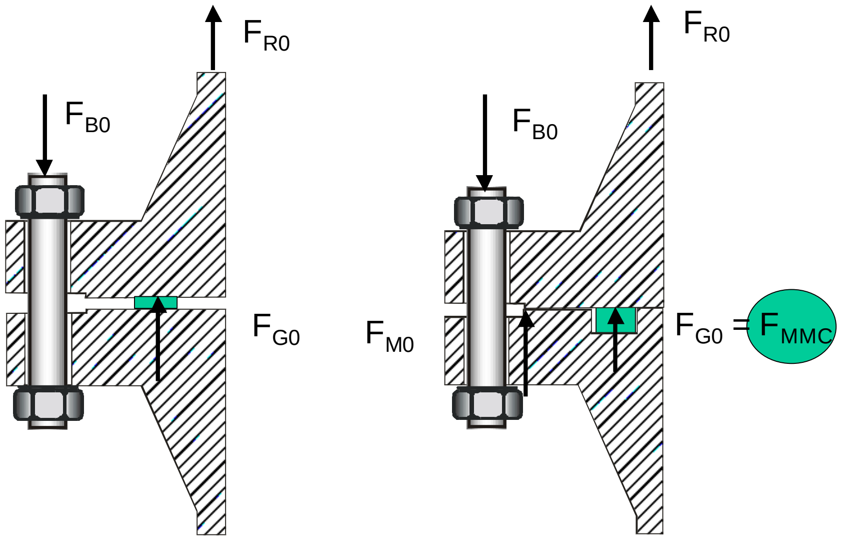


Fig. 2: Force balance in the assembly state for floating (left) and metal-to-metal contact type (right)

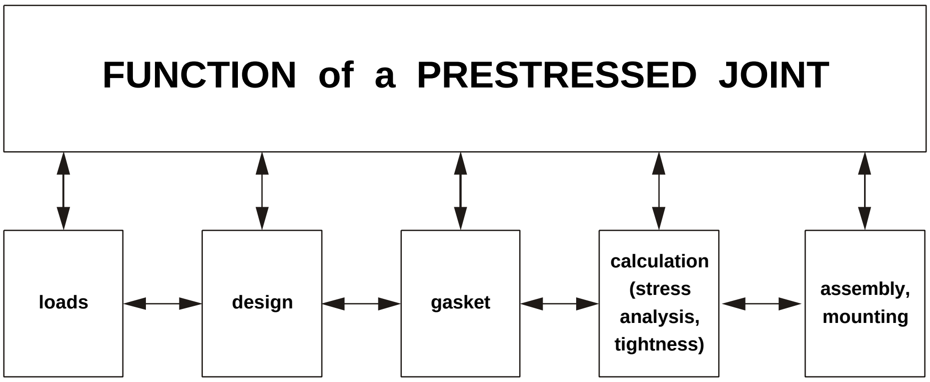


Fig. 3: Parameters affecting the correct function of flanged joints

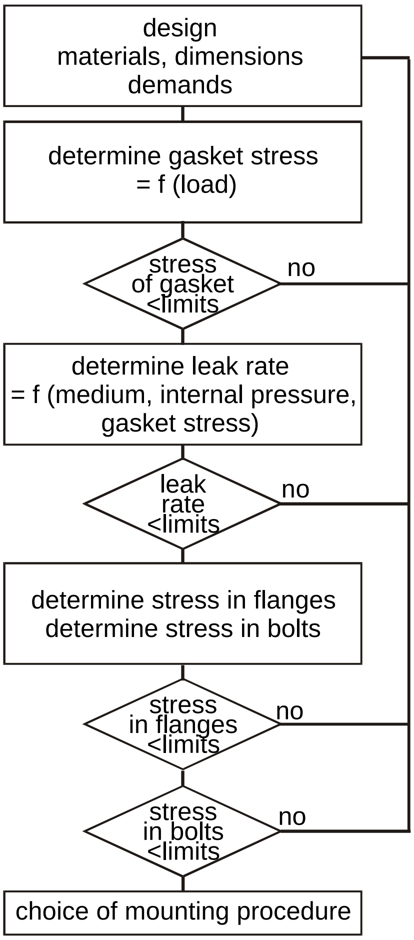
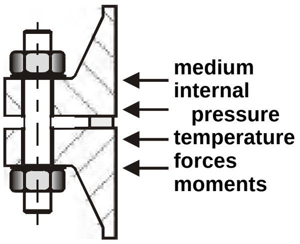
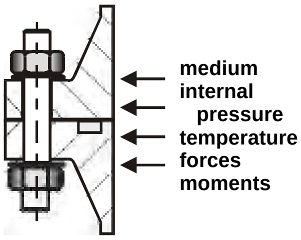


Fig. 4: General procedure for flange calculation

gasket factors prEN 13555	description
$Q_{MIN(L)}$	minimum assembly gasket stress
$Q_{SMIN(L)}$	minimum operation gasket stress
Q_{SMAX}(RT)	maximum assembly gasket stress
Q_{SMAX}	maximum operation gasket stress
E_{0}, K_{I}	elastic recovery intercept, slope
g_{C}	creep / relaxation factor





gasket factors	description
σ_{MMC}	minimum gasket stress to reach contact
$p_{MMC/L}$	maximum pressure for tightness class L
g_{C}	creep / relaxation factor

Fig. 5: Gasket factors for use in calculation (top: floating gasket type; bottom: metal-to-metal contact type)