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Failure analysis of bolted steel flanges

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This paper presents results from nonlinear FE-calculation of bolted steel ring flange connections. Different FE-models for a segmental approach and calculation of the total flange are presented and the results are discussed in regard to the structural design calculation.

1. INTRODUCTION

Ring flanges are used in standard connections in tubular structures, especially in towers for wind energy converters (WEC). Towers can require three or more flanged connections throughout their length, which contribute significantly to the total cost. The structure must be checked for both fatigue and failure conditions, and enhanced FE calculation methods are appropriate.

2. SIMPLIFIED CALCULATION METHOD

In Germany the design of ring flange connections is generally performed by using an approach of Petersen [1]. This calculation model is based on the behaviour of the individual segment of flange which contains the bolt with the maximum tensile force (Fig. 1). The load bearing capacity can simply be calculated with the plastic hinge theory considering three failure mechanisms of the critical segment (Fig. 2).

This local concept ignores the fact that the opening of the connection and plastic deformation will lead to some redistribution of forces. Consideration of the total flange enables this redistribution to be taken into account.

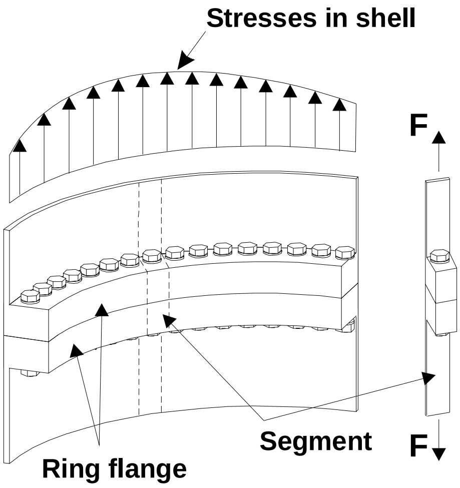


Fig. 1: Typical ring flange with preloaded high-strength bolts

For that reason investigations are carried out with two different 3D-FE-models: Firstly a model of a single segment with one bolt to verify the simplified calculation method and secondly a model of the flange as a whole to take advantage of the global carrying capacity of the connection.

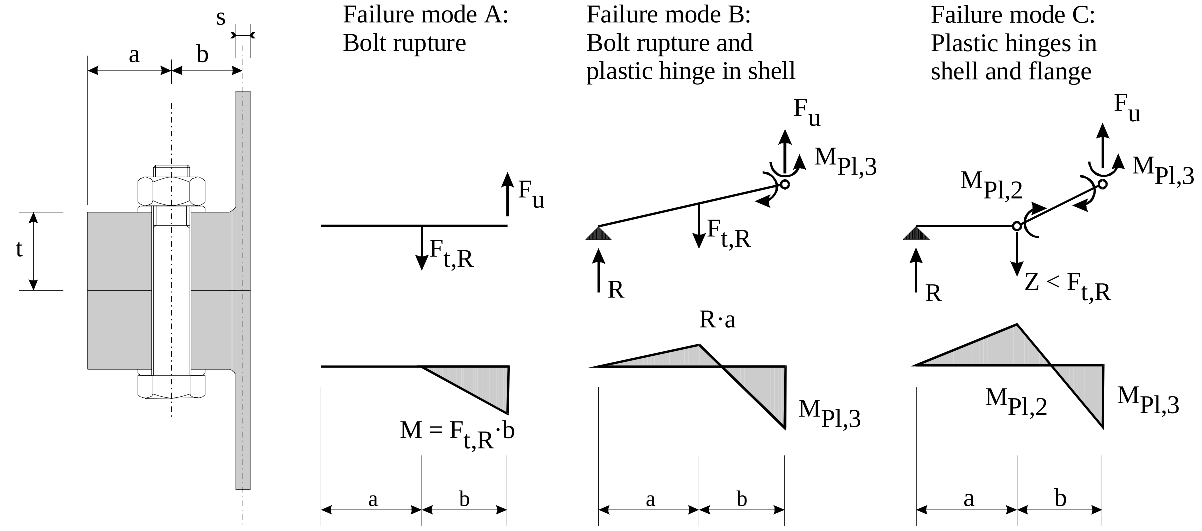


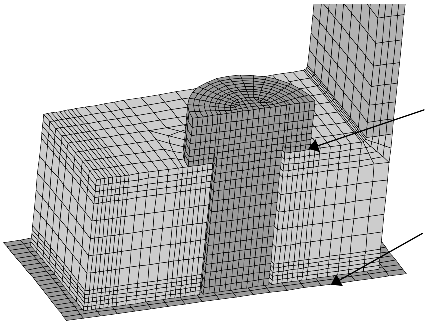
Fig. 2: Failure modes of the simplified calculation method acc. to Petersen [1]

3. FE-ANALYSIS OF THE SEGMENT

3.1. Description of the 3D-FE-Model

The calculations were carried out with the commercial code ANSYS V5.5. Different variants concerning contact modelling as shown in Fig. 3 have been compared for the segment model. The first variant uses contact elements between washer and flange and between the flanges in the plane of symmetry. The connection between bolt head and washer is assumed to be rigid. As an alternative the second variant omits the contact elements, providing a rigid connection between washer and flange, along with Link-elements in the plane of symmetry. The computational time is less for this second variant.

The elasto-plastic analysis uses a bi-linear stress-strain relationship with characteristic values for the yield strength of the flange and the shell and a modified yield strength for the bolt. As the FE-Model for the bolt uses a constant cross-section over the total length including the thread, the yield strength is modified as such that the plastic resistance of the bolt equals the characteristic tension resistance according to Eurocode 3 [2, Table 6.5.3]. Safety factors are not taken into account because the results are to be compared with experimental data.



Variant 1:	Variant 2:
Contact elements between washer and flange	Rigid connection between washer and flange
Contact elements with target surface in plane of symmetry	Link-Elements in plane of symmetry

Fig. 3: 3D-FE-Models of the flange (segment model)

The FE-Model with contact elements has been verified by comparison with experimental results from Wanzek [3] and Petersen [1]. The T-Stub-tests presented by Wanzek serve as an example for thin flanges up to 20mm. The tests from Petersen [1] cover medium flange thicknesses in the range of 20 to 50mm. The FE-Model with contact elements shows good agreement for all flanges, so that model can be rated as reliable.

3.2. Parametric Study for different flanges (Segment Model)

A parametric study has been carried out to show differences between simplified calculation and the two FE-variants for the segment. The geometry of a WEC-flange was used as a basis from which different flanges were derived. Fig. 4 illustrates the flange geometry. The original flange has a thickness of 65mm.

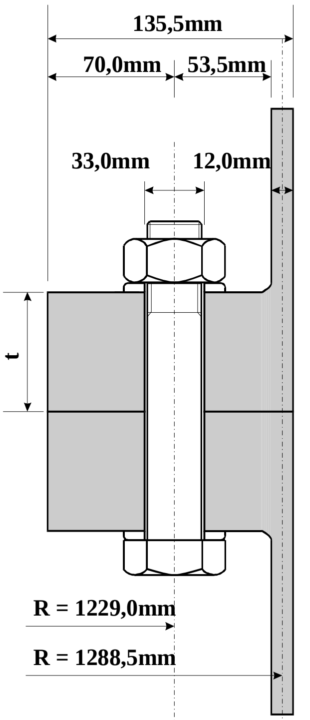
The results from the study are summarized in Table 1. It can be seen that the simplified model is always safe and gives good results for flange thicknesses above 50mm when failure mode B (see Fig. 2) is decisive. However the load carrying capacity is underestimated for thinner flanges. For a flange thickness of 25mm the prediction of the simplified model is less than 50% of the result from the nonlinear FE-calculation.

The failure modes obtained from the simplified calculation method agree with FE-results for thick flanges. In the medium thickness range the failure modes and load carrying capacity differ significantly.

Comparing the two FE-variants it can be stated that the calculated ultimate loads from the variant without contact elements are too high for thin flanges, while results agree almost exactly for thick flanges.

Flange	**Simplified method**		**FE-calculation**	
thick-ness t	**Failure load**	**Failure mode**	**with contact elements**	**without contact elements**
[mm]	**[kN]**	**[–]**	**[kN]**	**[kN]**
25	94,4	C	203	210
30	127,7	C	253	280
35	166,7	C	297	299
45	260,4	C	299	299
65	304,8	B	299	300
100	304,8	B	312	300

Table 1: Ultimate load acc. to different calculation methods



Bolts: **66 high strength bolts with ø30mm**
(M30 10.9) **f_y = 900 MPa**
f_u = 1000 MPa

Material Flange: f_y = 355 MPa

Fig. 4: Parameters of example

3.3. Enhancement of the simplified calculation method

In order to improve the calculation of carrying capacity for thin flanges with the simplified method as described in chapter 2 the failure mechanisms of the FE-calculations were analyzed. The detailed investigation of the stress distribution in the ultimate limit state shows that the bending resistance of the plastic hinge in the flange is supported by the moment contribution of the contact pressure resulting from the bolt's tensile force (Fig. 5). The prediction of ultimate carrying capacity from the simplified calculation acc. to Fig. 2 is too low, because only the remaining part of the flange (width c' in Fig. 5) is assumed to contribute to the plastic moment resistance. A better approximation is obtained if the contribution of the bolt's contact pressure is included in the calculation of the moment resistance. This additional share adds considerably to the overall resistance because of the dimensions of flanges for WECs with many closely arranged bolts. Formulas for an improved simplified calculation method are being derived and will be published soon.

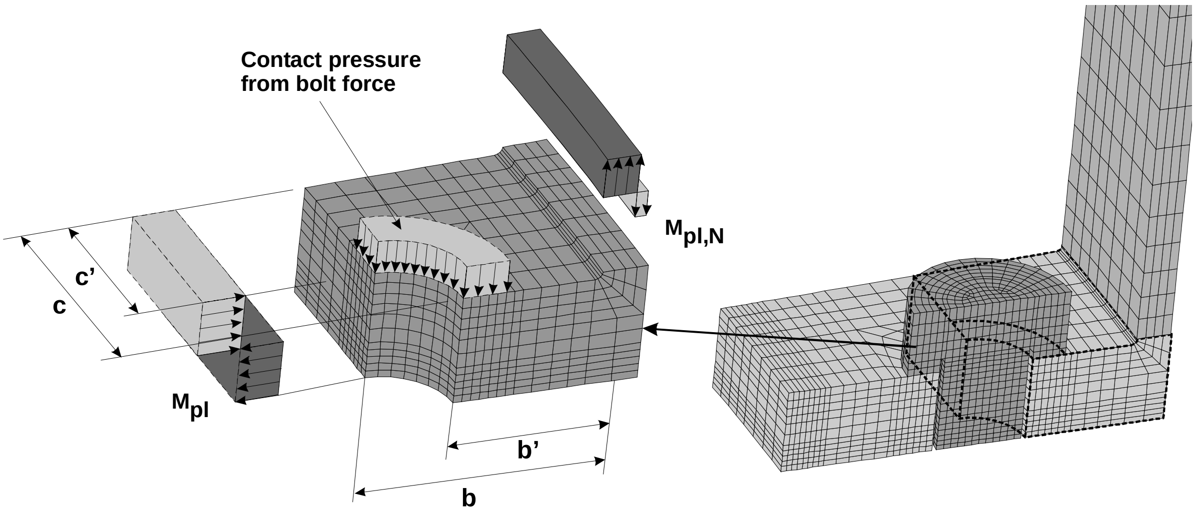
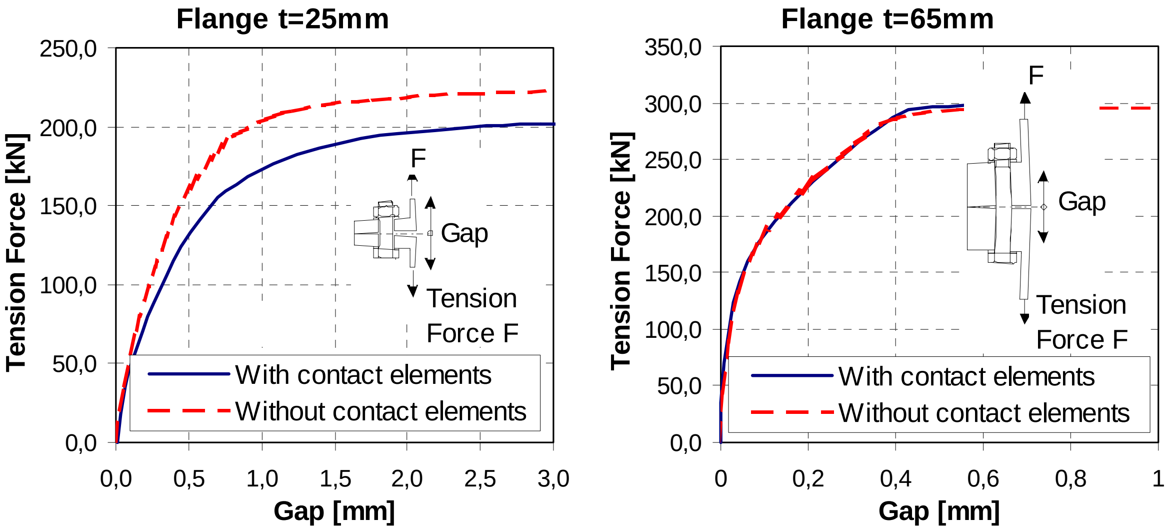


Fig. 5: Stress distribution in flange at ultimate limit state

3.4. Influence of model accuracy on deformation behaviour

The deformation behaviour of the two FE-variants for the segment is important for the generation of the total flange model. In section 3.2 it was shown that the prediction of ultimate loads of thick flanges can be performed with variant 2. For the total flange it has to be made certain that the model without contact elements predicts deformations accurately.

Fig. 6 shows load-deflection-curves for the different variants. It can be seen that the model without contact elements reacts too stiffly for the thin flange with t = 25mm, assuming that the deflections from the model with contact elements are correct. As this variant has been verified with experimental data, this assumption is acceptable. However, the deflections are in excellent agreement for the flange t = 65mm. The same applies to the bolt force so that the segment model without contact elements can be used to build up the FE-model of the total flange with a thickness of t = 65mm.



a) Comparison for flange t = 25mm b) Comparison for flange t = 65mm

Fig. 6: Influence of model accuracy on gap widths in dependency of tension force

4. FE-ANALYSIS OF THE TOTAL FLANGE

The total flange is generated by duplication of the segment model along the circumference. A length of 5000mm of shell is attached to the flange, so that redistribution of forces can take place. This model is used to determine bolt forces and stresses in shell and flange under pure bending for the total connection.

Fig. 7 illustrates the bolt forces for the segment model and the highest loaded bolt from the total flange model. The bending stress from the total flange has been converted to a tension force by multiplying the maximum bending stress with the appropriate area from the shell wall. It can be seen that the bolt forces are in excellent agreement for low tension forces (resp. low bending stress). For any given opening of the connection, the bolt force in the total flange is below that found from the segment model. This behaviour is to be expected because the parts of the flange which are opening have a lower stiffness than the parts that are still in contact.

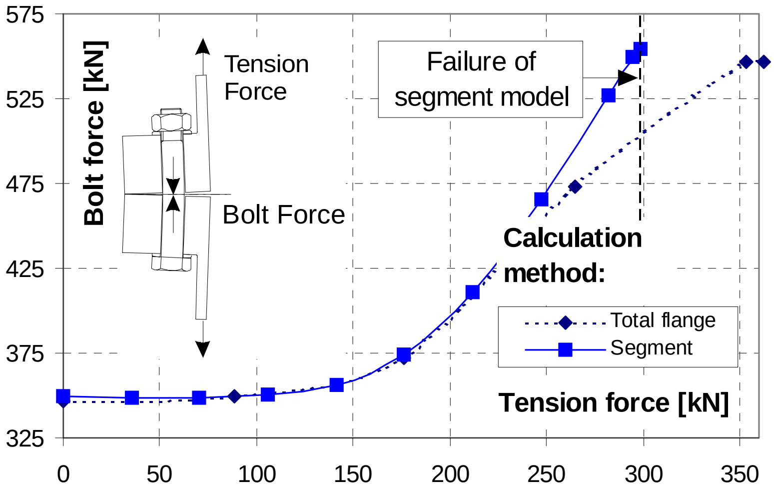


Fig. 7: Bolt force in dependency of tensile force

The opening of the flanges also causes some redistribution of stresses in the shell. The stresses on the tensile side are lower than according to linear theory, while the stresses at the compressed side remain virtually identical. Therefore, the neutral axis is offset to the compression side, but the differences regarding the decrease of the maximum stresses on the tensile side between FE-Model and beam theory are rather small (about 10% for the calculated geometry). A significant decrease of stresses and therefore bolt forces on the tension side, as determined by Ebert and Bucher [4] from a spring model, does not occur.

The carrying capacity of the total flange is considerably higher than that of the segment. This increase of load bearing capacity is accompanied by significant plastic deformation in the bolts. The magnitude of strains depends on the geometric variables of the flange, such as number of bolts and flange dimensions. The actual carrying capacity will therefore not be limited by strength criteria but by allowable deformations and strains, particularly in the bolts. Details on required plastic deformations will be made available by future research works at the University of Hannover.

5. CONCLUSION

Different methods to calculate the ultimate carrying capacity of bolted ring flange connections are discussed. It could be shown that a simplified design method proposed by Petersen [1] for flange segments gives good results for thick flanges, but underestimates the capacity for thin flanges. A modification of the calculation method has been derived which attains better results for thin flanges.

The carrying capacity estimated on the basis of a linear distribution of loading around the flange, taking the attainment of ultimate capacity at an individual segment as defining failure, is significantly less than when the flange is fully modelled, due to redistribution. The increase in calculated loading capacity is in general limited by the allowable plastic strain of the bolts.

It is considered that the work described in this paper will lead on to significant economies in flange joint costs, which will assist in making wind power generation more profitable.

REFERENCES

1. Petersen, C.: Stahlbau (Steel Construction), 3. Edition: Vieweg-Verlag. Braunschweig 1997 (in German)
2. DIN V ENV 1993-1-1: Eurocode 3: Design of Steel structures; Part 1-1: General rules and rules and buildings. European Committee for Standardisation CEN. Brussels 1992.
3. Wanzek, T.: Zu Theorie, Numerik und Versuchen verformbarer Anschlußkonstruktionen. Berichte aus dem Konstruktiven Ingenieurbau der Universität der Bundeswehr München 97/7. München 1998 (in German)
4. Ebert, M.; Bucher, C.: Stochastische nichtlineare Untersuchung vorgespannter Schraubenverbindungen unter Windeinwirkung (Stochastical nonlinear study of preloaded bolts under wind load). Braunschweig 1997 (in German)