Effect of the Wall Thickness Tolerance on the Results of detailed FEM-Calculations

Wieland Holzer, Werner Wolf

TÜV Industrie Service, Munich

ABSTRACT

In this paper we review the effect of the wall thickness tolerance of piping components like tees or bends on the results of detailed FEM-calculations. Therefore we look on the part of the wall thickness from the designing process to the calculation of primary and secondary stresses considering the equations given in the design codes and the stresses calculated by detailed FEM-analysis.

If we use the methods above we have always to check if the maximum permissible stresses and strains are met. For tees and bends this is often difficult when the well known equations given in the design codes are used, because the stress intensification factors are often considered to be overly conservative. Therefore for components, for which the maximum permissible stresses and strains are not met by using the equations give in the design codes, it's common to carry out detailed FEM-calculations.

The wall thickness which should be used for the equations given in the design codes is the nominal wall thickness or the average wall thickness, respectively the effective average wall thickness. This definition of the wall thickness has also to be taken into account for the FEM-calculations. Another very general criterion of the design codes and the general regulations is that for the whole lifetime of the power plant reductions of the wall thickness caused by corrosion or erosion or by the grinding of welds to prepare them for the periodic testing have to be taken into account.

According to the current state of technology detailed FEM-calculations – considering correct constraints - are the most common method for obtaining realistic stress and strain results, because with common computers and FEM-programs there is no longer any problem to model realistic FEM-geometries with ~100.000 or more degrees of freedom. So in the calculation process the remaining important safety margins are the realistic material behaviour and the definition of the operating conditions. That's why the FEM-calculations have to be done very carefully, especially if elastic-plastic methods are used. For some examples these effects are shown in this paper. For bends the results can be compared with the interesting method of reduced stress indices which is still under discussion.

Therefore in a kind of prototyping we only use parametric FEM-models. So it's easy to investigate the component behaviour with several wall thicknesses. In case of remaining plastic strains of about 0.2%-1.0% for normal operating conditions considering the minimum design wall thickness we investigate in our evaluation process if the plastic deformation is progressive. For such components it's advisable to consider them in the non-destructive testing and load monitoring programs. So if unexpected loads occur or the erosion or corrosion rates are unexpected high, it's possible to adapt the parametric FEM-models and carry out a stress and strain analysis just in time.

INTRODUCTION

For new piping systems or components, first of all, the wall thickness has to be determined. In the designing process all the designing loads – pressure, temperature and mechanical loads - shall be taken into account. The formulas for the determination of the minimum required wall thickness for pipes and shells are given in the design codes. See, for example, ASME-Code Section III, Division 1, Subsection NB and NC [1] and KTA 3201.2 [2] and 3211.2 [3]. An additional wall thickness for corrosion or erosion and the manufacturing tolerance range should be considered. The following equation is well-known for the determination of the minimum thickness of a pipe wall required for design pressure:

$$t_m = \frac{PD_0}{2(S_m + Py)} + A \qquad (1)$$

In the ASME-Code Section III, Division 1, Subsection NB and NC [1] it is explained that the additional thickness A should be considered for possible material removal for example by erosion or corrosion. It's also explained that the manufacturing tolerance must be taken into account.

ANALYSIS OF PIPING SYSTEMS

Analysis of Piping System Design according to the Equations given in the Design Codes

In order to evaluate the complete piping system, it shall be analyzed between anchors for the effect of thermal expansion, weight and other permanent and occasional loads. Well-known equations for evaluating the piping systems are also given in the design codes. For satisfying the primary and secondary stress limits the following equations shall be met:

$$B_1 \frac{PD_0}{2t} + B_2 \frac{D_0}{2I} M_i \leq 1.5 S_m \tag{2}$$

$$C_1 \frac{P_0 D_0}{2t} + C_2 \frac{D_0}{2I} M_i + C_3 E_{ab} \left| \alpha_a T_a - \alpha_b T_b \right| \leq 3 S_m \tag{3}$$

In these procedures it's clearly defined which wall thickness shall be used. According to the ASME-Code [1] the nominal wall thickness shall be used. According to the design code KTA 3201.2 [2] and 3211.2 [3] the average wall thickness respectively the effective average wall thickness shall be used for the analysis of the mechanical behaviour.

By using the wall thickness as defined above the stiffness and the bending moments are considered to be accurate enough on the average. So according to the experience this procedure can be seen as a proven compromise because the expenditure to consider the real wall thickness for each pipe component and to consider all possible erosion or corrosion rates wouldn't be acceptable. If the stress intensities in the equations above - considering the stress indices - are met for all the relevant load sets, the piping system can be considered as being safe.

Detailed Methods for the Analysis of Pipe Components

If it's not possible to meet the stress intensity limits given in the equations above, there are several other possible evaluation methods according to the design codes. This is for example the FEM-method for detailed elastic stress analysis, the limit analysis, the plastic analysis or the shakedown analysis. For bends interesting approaches for reduced stress indices are discussed in [4]. The other evaluation methods can be done with most of the available highly sophisticated FEM-Codes. In any case the acceptability of the method must be shown and it must be clear if the three influence factors

- loads,
- material behaviour
- wall thickness

are considered correct respectively conservative. Besides on the long term it must be taken into account that in the most (German) inspection instructions for the periodic non-destructive inspection of pipe components wall thickness reductions are considered as being permissible as long as the measured value is not less than 90% of the nominal wall thickness. Then according to the inspection instructions it's not necessary to check if the wall thickness is local or not. So we take a look on the effect of the three influence factors above on the results of FEM-calculations. In this paper the focus is on the wall thickness tolerance including manufacturing tolerance and corrosion and erosion rate.

USUAL FEM-CALCULATION FOR PIPING COMPONENTS

Only if the FEM-models are detailed enough there can be obtained reliable results with the methods mentioned above. Because by using these methods the behaviour of the components can be calculated realistic, it's important to know the influence of the three factors above.

In this paper we investigate the influence of the wall thickness with the collapse load method because this method is very easy to use and one of the most used methods. For the evaluation of the influence of the wall thickness on the results a fictive elastic-plastic material behaviour was used. This fictive stress-strain-curve is the inverse definition of the allowable design stress intensity value S_m. For the reason of simplification in this paper we used S_m=100 MPa.

FEM-Models

Bends with the parameters shown in table 1 and a pipe tee are considered. For the bends with this parameters typical cross sections and a wide range of the characteristic bend parameter h is considered. The definition of the characteristic bend parameter h is given in the Nomenclature section. For pipe tees only one example is presented in this paper. The principle issues can be shown with this example, but for general statements some more pipe tees have to be investigated to cover the important geometrical parameters of a pipe tee.

Table 1: Investigated bends

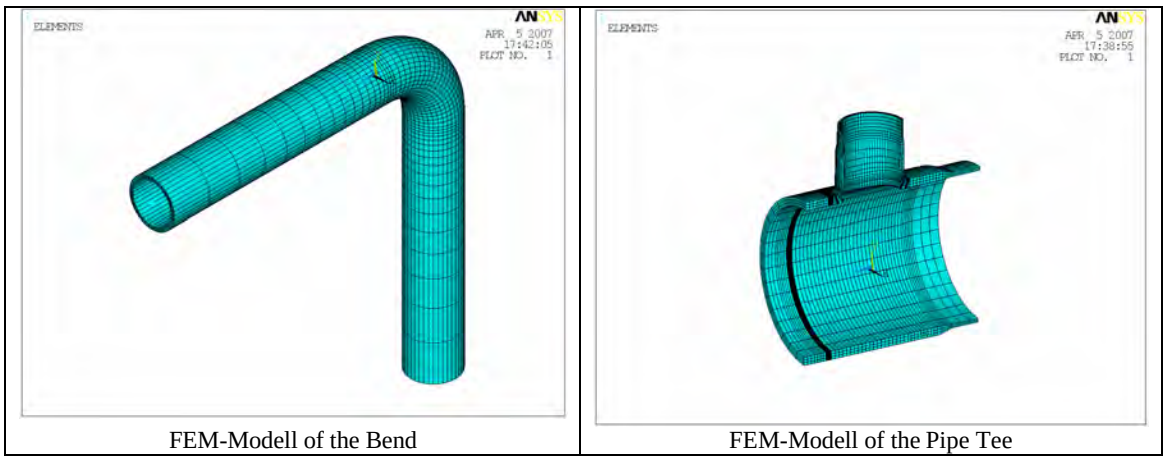
Bend No.	D_o [mm]	R [mm]	t [mm]	t_{tol} [%]
1	114,3	152,5	2	10
2	273	381	6,3	15
3	406,4	610	8,8	15
4	168,3	228,5	4,5	15
5	114,3	152,5	3,6	10
6	88,9	114,5	3,2	10
7	60,3	76	2,9	10
8	114,3	152,5	6,3	10
9	60,3	76	4	10
10	76,1	95	5,6	10
11	114,3	152,5	8,8	10
12	60,3	76	5,6	10

The data of the investigated pipe tee is shown in table 2.

Table 2: Investigated pipe tee

Tee	D_i [mm]	t [mm]	t_{tol} [%]	r_i [mm]	r_o [mm]
Pipe	624	35	10		
Branch	255	17	10		
Fillet			-	6	18

The FEM-program ANSYS 11.0 [5] was used for the FEM analysis of the bends and the pipe tee. The parametric FEM-models are shown in figure 1. For the FEM calculations 3-dimensional solid elements with linear displacement behaviour were used.



FEM-Modell of the Bend FEM-Modell of the Pipe Tee

Figure 1: FEM-models bend and pipe tee

Collapse Load Analysis

For the bends listed in table 1 we determined the collapse pressure and the collapse bending moment. At first we considered the nominal wall thickness. The ratio of the collapse bending moments of the bends and the collapse load of the

straight pipes with the same cross section can be compared with the results given in [4]. In [4] the equation 4 - ratio of the collapse moment of the straight pipe to the collapse moment of the component - is suggested as a possible definition for the stress index B_2 for bends.

$$B_{2,[4]} = \frac{M_{CL,straightpipe}}{M_{CL,component}} \tag{4}$$

As the result of the evaluation of the FEM-data carried out in [4] some equations related to the characteristic bend parameter h are given in [4] for this definition of B_2. As shown in figure 2 our results are in accordance with the results given in [4]. Figure 2 shows that our results and the results given in [4] are clearly less than the B_2-equation given in the codes. In the codes B2 is defined as

$$B_{2,Code} = \frac{1{,}3}{h^{2/3}} \geq 1 \tag{5}$$

If the characteristic bend parameters depend on the nominal wall thickness, but a bend with a wide-area wall thickness reduction, for example caused by erosion or corrosion, has to be evaluated, a higher B_2-factor could become relevant. Some examples for the collapse load ratio minimum-wall-thickness-bend/nominal-wall-thickness-straight pipe is also shown in figure 2. Our results shown in figure 2 are all obtained for in-plane-bending, so that the influence factor “load” can only be considered in a conservative manner. But the influence factor “wall thickness” should carefully be monitored by a non-destructive inspection program if wall thickness reduction – for example caused by erosion or corrosion – could not be excluded and reduced stress indices are used for the evaluation of components with highly loaded components. Nevertheless the international discussion on the reduced stress indices should be pursued because with this method a practical way for the evaluation of highly loaded components could be established.

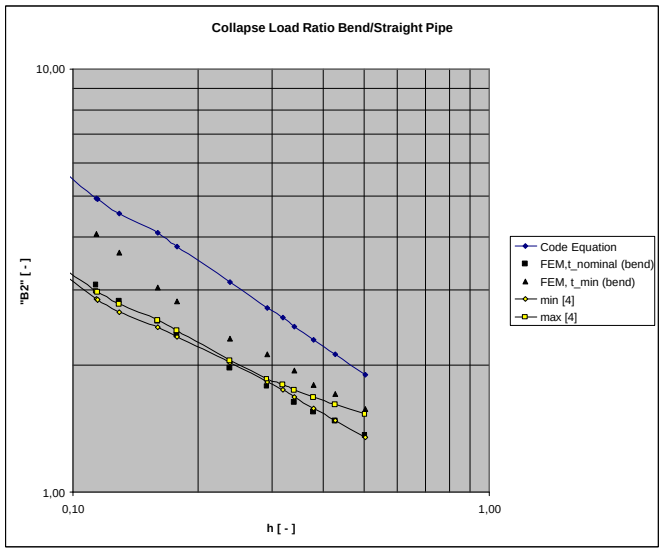


Figure 2: Evaluation of the collapse load using equation 4

For the pipe tee with the geometry data given in table 2 we also determined the collapse pressure and the collapse bending moment. For the first calculation we also considered the nominal wall thickness. For the second step we considered 90% of the nominal wall thickness. The results show, that the collapse load of the FEM-model considering the reduced wall thickness is more than 10% less compared to the collapse load based on the nominal wall thickness. The German codes [2] and [3] give the following equation for the index B_{2A} for the pipe tee shown in table 2. If there are bending moments on the main pipe which could not be neglected, then the index B_{2H} for the main pipe also has to be taken into account:

$$B_{2A} = 0{,}5\left\{3 \cdot \left(\frac{d_{Hm}}{2s_{Hc}}\right)^{2/3} \cdot \left(\frac{d_{Rm}}{d_{Hm}}\right)^{1/2} \cdot \left(\frac{s_{Rc}}{s_{Hc}}\right) \cdot \left(\frac{d_{Rm}}{d_{Aa}}\right)\right\} \geq 1 \qquad (6)$$

If the branch is very long instead of the pipe cross section the branch cross section has to be considered in equation 6. The results of equation 4 and equation 6 are shown in table 3. For the FEM calculations the internal collapse pressure based on the nominal wall thickness was taken into account.

Table 3: B_2 for the Investigated pipe tee

Equation No.	6 (code [2] and [3])	4 nominal wall thickness	4 90% of nominal wall thickness
B_2 [-]	1,96	1,35	1,51

The comparison of the results shows that there is an influence of the wall thickness on the admissible load. Therefore the importance of the load determination process and the material behaviour considered in the FEM-analysis increases and it should be ensured that the correct wall thickness is monitored by the non-destructive inspection process.

Evaluation with a fictive elastic-plastic material behaviour

To evaluate the effect of the wall thickness tolerance on the integrity of the components the plastic strains could be estimated. Therefore we used the same FEM-models and identical loads as above. The material behaviour is defined by the following fictive stress-strain-curve based on the allowable design stress intensity value S_m=100 MPa which (for example for austenitic material) should meet equation 7 for higher temperatures. For lower temperatures $R_{0,2RT}/1{,}5$ an $R_{mRT}/3$ shall also be taken into account.

$$S_m = \min\left\{\left(\frac{R_{p0,2T}}{1{,}1}\right); \left(\frac{R_{p1,0T}}{1{,}5}\right); \left(\frac{R_{mT}}{2{,}7}\right)\right\} \qquad (7)$$

The considered stress-strain-curve is shown in figure 3.

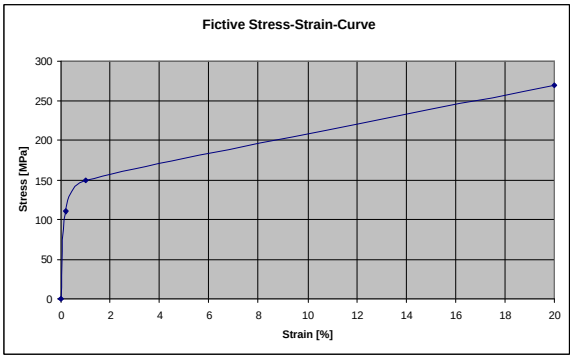


Figure 3: Fictive Stress-Strain-Curve for Estimating the Plastic Strain

For a first clarification if plastic strains and/or progressive plastic strains have to be considered for the components with a reduced wall thickness, the stress-strain-curve shown in figure 3 could be seen as conservative. Our FEM-results show that with the collapse loads obtained for the components with the nominal wall thickness the components with the reduced wall thickness show a plastic equivalent strain of about 0.2% to 1.8%. For the components with the reduced wall thickness the collapse loads obtained with the reduced wall thickness result in a maximum equivalent strain near 1.0% or less. For the

bends listed in table 1 the obtained equivalent plastic strains are shown in figure 4. For the pipe tee the obtained equivalent plastic strains are shown in figure 5.

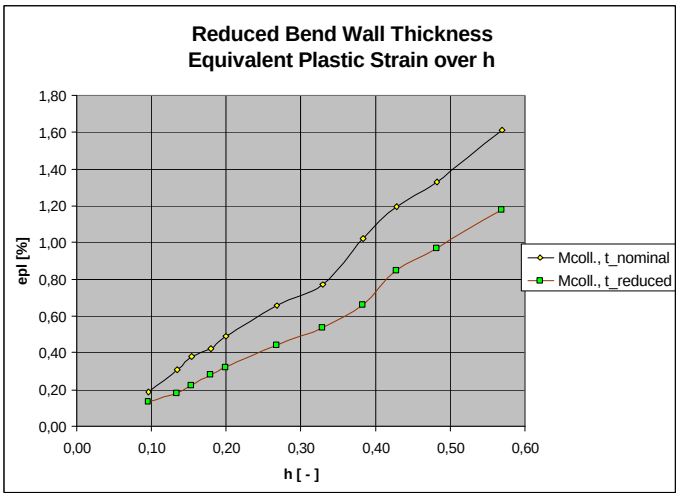


Figure 4: Equivalent Plastic Strain of the Bends

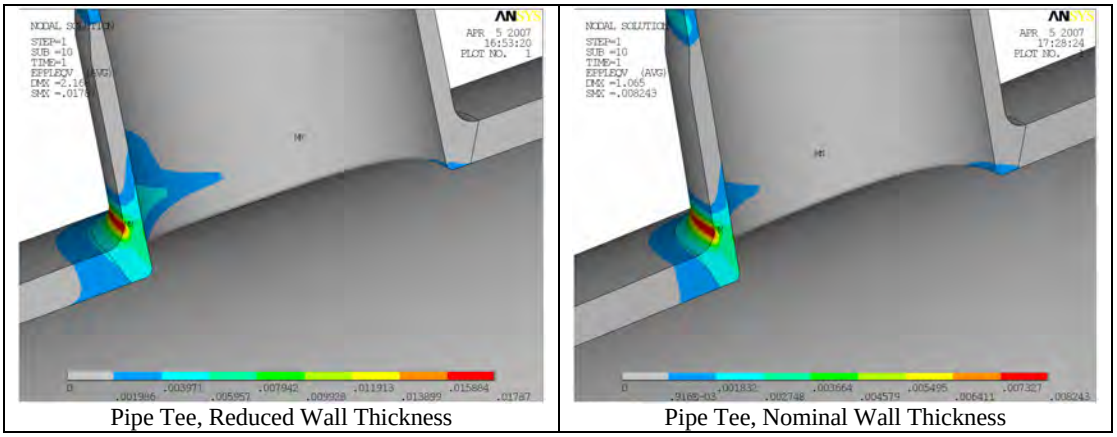


Figure 5: Pipe Tee, Equivalent Plastic Strain, 2/3 x $M_{bcoll,\ t\_nominal}$

RESULTS AND CONCLUSION

The FEM-calculations show that there is a clear effect of the wall thickness tolerance for piping components like tees and bends on the obtained plastic strains. With the loads which are admissible for the nominal-wall-thickness-components a plastic strain rate of approximately 0.2%-1.8% can be obtained considering the common wall thickness tolerances of about 10%-15%. But the exact value depends on the real geometry, the load situation and on the material behaviour.

With the variation of the wall thickness within its tolerance – considering an erosion or corrosion rate if necessary - and the fictive stress-strain-curve the wall thickness-related safety margin can be estimated. So it can be decided if the component should be considered in the non-destructive testing program to monitor the wall thickness and it can be decided if a more or less high sophisticated load monitoring system is necessary. The results also show that a possible progressive plastic strain should be taken into account, especially if it's not sure that the component wall is the nominal wall thickness. The results confirm the importance of the general statements in the codes that (for the normal operating conditions) it must be

ensured, that the plastic strains remain local and that the effects of plastic strain concentrations on the mechanical behaviour should be investigated.

Because according to the current state of technology detailed FEM-calculations – considering correct constraints - are the most common method for obtaining realistic stress and strain results, the safety margins of the considered material behaviour and the load determination process should be clear. That's why the FEM-calculations should be done very carefully and the constraints, loads, the wall thickness and the material behaviour should be considered sensible, especially if elastic-plastic methods are used.

So it can be concluded that the detailed FEM-analysis of high loaded components often is not a stand alone process but the FEM-results should be used to optimize the non-destructive and monitoring programs.

NOMENCLATURE

A = additional thickness to provide for material removed in threading, corrosion or erosion allowance
B_1 = primary stress index for pressure
B_2 = primary stress index for bending
C_1 = secondary stress index for pressure
C_2 = secondary stress index for bending
C_3 = secondary stress index (range of temperature at a gross structural or material discontinuity)
d_{Aa} = outside diameter (of branch)
d_{Hm} = mean pipe tee diameter
d_{Rm} = mean pipe diameter (connection the branch)
Di = inside diameter (of pipe)
D_o = outside diameter (of pipe)
E_{ab} = average modulus of elasticity of the two sides of a gross structural or material discontinuity
I = moment of inertia
h = characteristic bend parameter tR/r_m^2
M_i = resultant moment due to a combination of Design Loads or resultant moment which occurs when the system goes from one service load set to another
P = design pressure
P_0 = range of service pressure
R = nominal bend radius
$R_{p0.2}$ = tensile yield strength, 0.2% (RT: room temperature, T: load temperature)
$R_{p1.0}$ = tensile yield strength, 1.0% (RT: room temperature, T: load temperature)
R_m = breaking strength (RT: room temperature, T: load temperature)
r_a = fillet radius outside
r_i = fillet radius inside
r_m = nominal mean pipe radius
s_{Hc} = nominal pipe tee wall thickness
s_{Rc} = nominal pipe wall thickness (connection the branch)
S_m = allowable design stress intensity value
$T_{a,b}$ = range of average temperature on side a (b) of a gross structural or material discontinuity
t = nominal wall thickness
t_m = minimum wall thickness
t_{tol} = nominal wall thickness tolerance
$\alpha_{a,b}$ = coefficient of thermal expansion on side a(b) of a gross structural or material discontinuity
y = 0.4

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