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Development of an analytical calculation method for the design of thermoplastic flange systems

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In the course of environmental protection and the amendment of TA Luft, emissions from flange connections must be reduced (to L0.01). The design and calculation of steel flanges is easy to handle with the help of EN 1591-1 [3] and EN 13555 [4]. However, the standards mentioned are not suitable in their current form for thermoplastic sealing joints, such as those used in natural gas supply. For this reason, lengthy and cost-intensive tests must currently be carried out to verify tightness and strength.
The aim is therefore to develop a time-efficient and cost-effective analytical calculation method based on the existing standards. For this purpose, the energy-elastic material parameters of the steel must be replaced by viscoelastic material parameters of the thermoplastics and the calculation algorithm adapted accordingly. The problem is to be investigated with the aid of numerical structural simulations (FEM) and experimental investigations. This is an innovative contribution presenting a research project with high practical relevance for industry.

1 Presentation of the research gap

Protecting the environment and using fewer resources is more important than ever. Sealed joints in pipeline and tank construction produce relatively high emissions, which must be reduced as far as possible for the reasons mentioned above. These connections can be critical, especially in the chemical industry. Since 01.12.2021, for example, the new "Technical Instructions on Air Quality Control (TA Luft)" [2] have come into force and must be implemented. As a result, sealing connections made of thermoplastics, which are used in natural gas pipes, for example, are becoming more important, as proof of tightness must be provided. At present, it is only possible to verify the tightness of thermoplastic sealing joints by experimental means to a very limited extent, see [6]. Experimental proofs are both cost-intensive and can only be transferred to other sizes of sealing elements to a limited extent.

2 Target definition

The aim is to develop a cost-effective, quick analytical calculation method for verifying the tightness and strength of thermoplastic flange systems. Based on an existing set of rules for metallic sealing joints (EN1591-1) and taking into account the special viscoelastic and thermal material properties of thermoplastics, the energy-elastic material parameters of steel must be replaced by the viscoelastic material parameters of thermoplastics and the calculation algorithm adapted accordingly. In order to adapt the analytical calculation method to the special features of the mechanical and thermal behavior of thermoplastics, both extensive experimental investigations and FEM analyses are required for the ultimately necessary modification of the calculation algorithm and the validation of the algorithm.

3 Methodological considerations

The following diagram provides an overview of the planned methodology and the interrelationships between them:

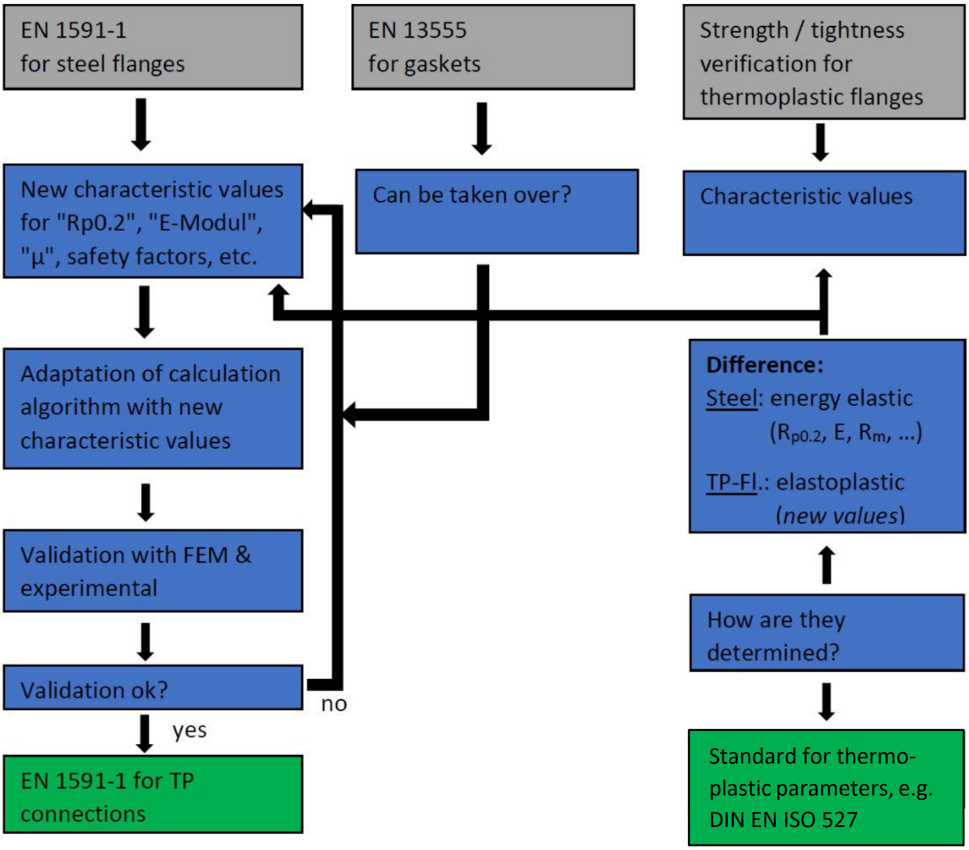


Figure 1: Diagram of the planned procedure

This is based on the standards for the design of steel flanges, marked in gray in Figure 1. In addition, research work was carried out to model the demanding material behavior in the FEM software. An elementary component of this is to model the creep behavior. The phenomenon in flange-connections is usually referred to "creep-relaxation". This is responsible for the decrease in surface pressure on the seal. The analytical calculation algorithm is to be adapted with the help of the simulation results and on the basis of the experimental findings. In the course of the experimental tests, the focus will be placed on investigating the thermoplastic material and its characteristic values.

After adapting the calculation method, the investigations and simulations can be reused to validate the analytical approach. This allows the possibilities and limits of the developed method to be demonstrated and evaluated.

In addition to the simple and cost-efficient design method, optimization potentials for the future can also be better identified and exploited.

4 Current status

For the numerical consideration of the problem, it is necessary to define the creep in the material properties separately using a creep model. Isochronous stress-strain curves can be used as a database for this purpose. Literature values can be found for selected materials. If this is not the case, time-consuming tensile creep tests must be carried out. This involves applying a constant stress to a tensile specimen and documenting the strain at regular intervals. By repeating the measurement at different loads, an isochronous stress-strain diagram can be created, just like in figure 2.

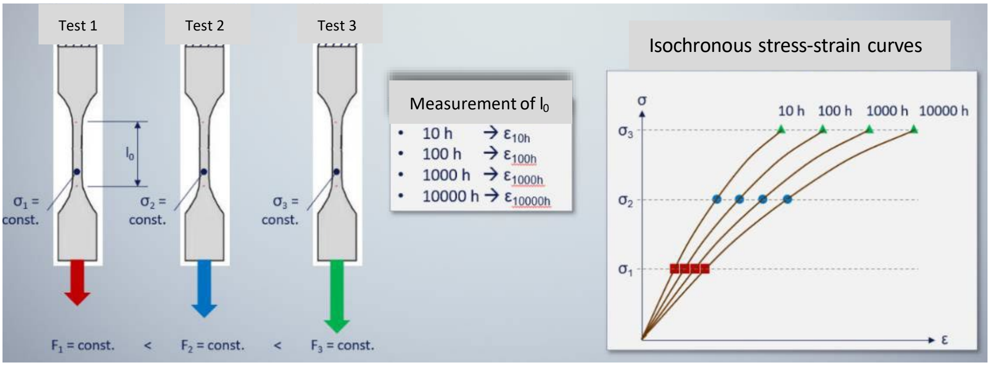


Figure 2: Illustration of creep tensile tests to create isochronous stress-strain curves [5]

As can be seen from [5], it is important to note that the test includes all strain components, which are composed as follows:

$$\varepsilon_{ges} = \varepsilon_{el} + \varepsilon_{pl} + \varepsilon_{cr} \quad (1)$$

Elastic and plastic, time-**in**dependent strains

Time-dependent creep strain

To determine the creep strain, it is therefore necessary to subtract the elastic and plastic strain. The proportions can be determined experimentally using the tensile test in accordance with DIN EN ISO 527.

The creep strain can now be calculated using the **Norton-Bailey** model, for example:

const. Parameter A, n, m

$$\varepsilon_{cr} = A \cdot \sigma^n \cdot t^m \tag{2}$$

Tension

Load time

According to [5], the elastic and plastic components of the strain can be modeled using the **Ramberg-Osgood model**, for example:

$$\varepsilon_{el,pl} = \frac{\sigma}{E} + K\left(\frac{\sigma}{E}\right)^p \tag{3}$$

The complete mathematical description of the isochronous stress-strain curves is thus carried out via:

$$\underbrace{\varepsilon = A \cdot \sigma^n \cdot t^m}_{\varepsilon_{cr}} + \underbrace{\frac{\sigma}{E} + K\left(\frac{\sigma}{E}\right)^p}_{\varepsilon_{el} + \varepsilon_{pl}} \tag{4}$$

Time-dependent creep strain

Time-independent strains

σ, t: freely selectable, e.g.

σ = 10, 20, … , 60 MPa

t = 10, 100, …, 100 000 h

$$\varepsilon = A \cdot \sigma^n \cdot t^m + \frac{\sigma}{E} + K\left(\frac{\sigma}{E}\right)^p$$

A, m, n:

Unknown parameters

E, K, p:

Previously calibrated (known) parameters

Using the model calibrated in this way, the bolt force relaxation due to creep of the thermoplastic material could be determined as follows:

First, the stresses in the component are determined, e.g. with the help of an FEM simulation. Figure 3 shows the von Mises comparative tension in the collar.

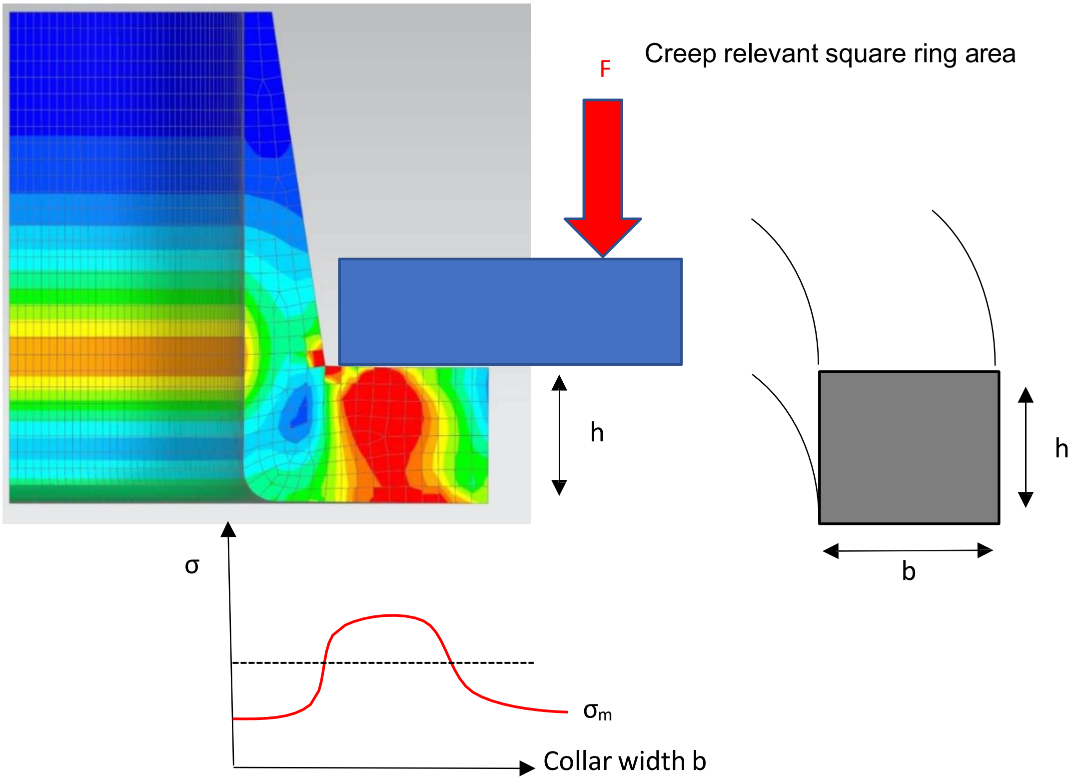


Figure 3: Simulative stress distribution in the flange collar

The change in length due to creep then results in:

$$\Delta l = \varepsilon_{cr} \cdot h \qquad (5)$$

Notice that the influence of the circumferential rotation of the loose flange on the mechanical behavior is not considered in this first calculation approach.

The creep strain can then be determined using the Norton-Bailey model:

$$\varepsilon_{cr} = A \cdot \sigma^n \cdot t^m$$

with calibration of A, n, m via isochronus stress- strain diagrams (parameter fitting)

$$\varepsilon_{cr} = f(\sigma, t, T)$$

The resulting bolt force relaxation can then be read approximately from the tension diagram as shown in Figure 4, when rotation is again disregarded.

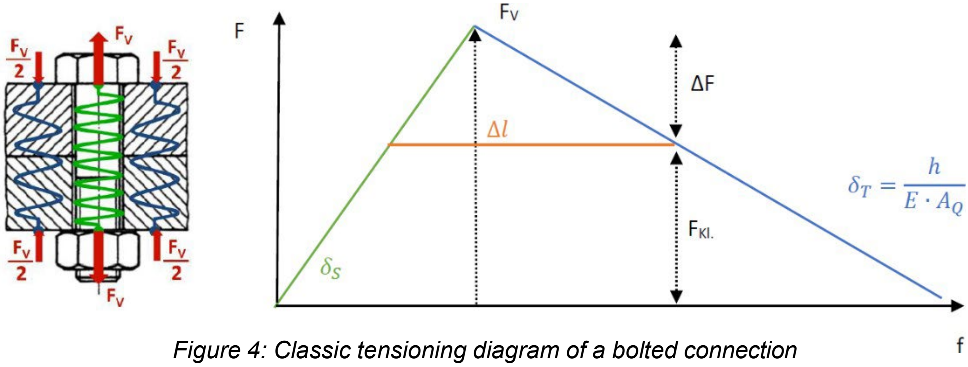
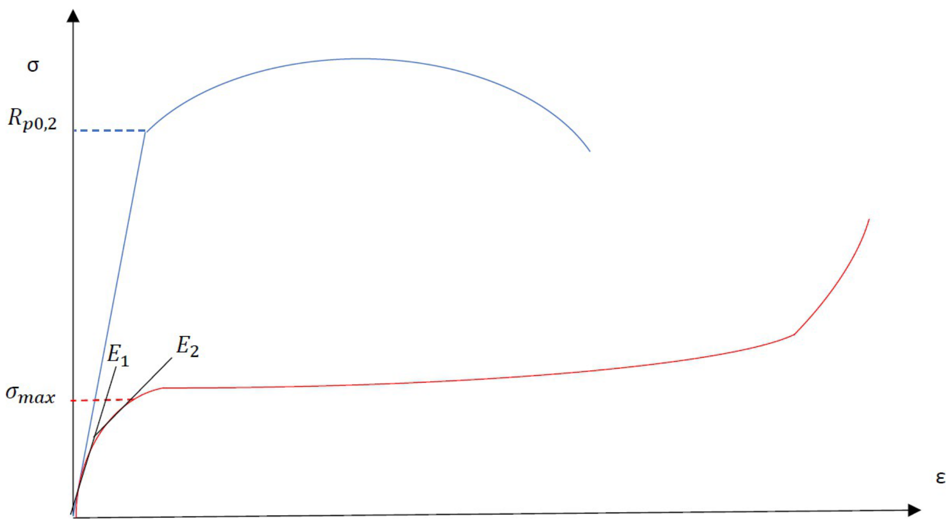


Figure 4: Classic tensioning diagram of a bolted connection

The residual surface pressure of the gasket results in: $P_{Rest} = \frac{F_{Kl.}}{A_G}$ (6)

In order to test the transferability of tensile tests (according to DIN EN ISO 527) to the real application in the flange, compression tests in the AMTEC test bench [1], as shown in Figure 6 and 7, are also planned. The schematic test setup is shown in figure 5. The AMTEC test bench is a leakage test rig that can usually also be used to determine the gasket characteristics in accordance with DIN EN 13555. In addition to the hydraulic cylinder and the heatable test plates, the test bench offers integrated force and displacement transducers as well as the option of leakage measurement using the pressure drop method or a helium mass spectrometer.



$$\sigma_{max} = f\ (T, t, \varepsilon)$$
$$E_n = f\ (T, t, \varepsilon)$$
$$\alpha = f\ (T)$$

on the flange

$$\sigma_{Fl.} = \sigma_{Pressure,Fl.} + \sigma_{Bending,Fl.}$$

Equivalent stress

Tensile test on specimen bar

$$\sigma_{Equ.} = \sigma_{Tension,Specimen} = \sigma_{Fl.}$$

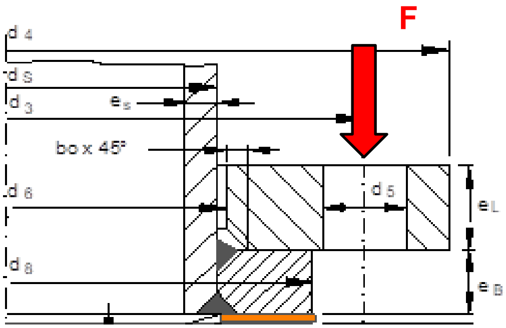


Figure 5: Schematic test setup for determining compressive stresses to check transferability to standard experiments [1]

The long-term goal is to determine the required material parameters using simple standard tests where possible and to convert them to real-life conditions. Whether and how such a conversion is possible is checked with the compression test. Table 1 below clearly shows the pairings for the first tests.

Table 1: Test plan for the compression tests in the AMTEC test rig

	Flange collar	Gasket	Temperature	Load
1	Polypropylen	NBR	21 °C	Short term
2	Polypropylen	EPDM	21 °C	Short term
3	Polypropylen	NBR	80 °C	Short term
4	Polypropylen	NBR	21 °C	Long term (100 h)
5	Polypropylen	NBR	80 °C	Long term (100 h)
6	Polyethylen	NBR	21 °C	Short term
7	Polyethylen	EPDM	21 °C	Short term
8	Polyethylen	NBR	60 °C	Short term
9	Polyethylen	NBR	21 °C	Long term (100 h)
10	Polyethylen	NBR	60 °C	Long term (100 h)

According to the current state of knowledge, the sandwich structure can be treated very similarly to a test specimen in DIN EN 13555 and the results can be applied in DIN EN 1591-1.

Figure 6: Experimental setup for carrying out the compression tests

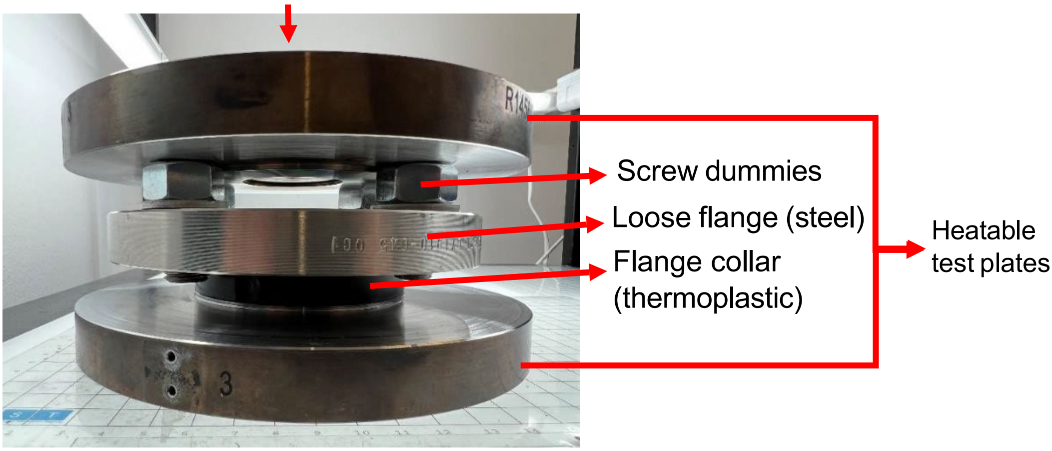


Figure 7: Sandwich structure of the test specimens, in accordance to [7]

5 Summary and Conclusion

In conclusion, it can be said that the investigation of thermoplastic flange systems is long overdue due to their increasing use and is now also gaining economic significance with the amendment of the TA Luft. The same applies to the increasing demands of climate protection. This conference paper is part of a larger research project and therefore initially reflects the current status of this project. In the long term, a draft standard based on EN 1591-1 and EN 13555 for the analytical calculation of thermoplastic flange systems is to be developed in order to reduce time-consuming and cost-intensive tests. The main difficulty lies in the consideration of the viscoelastic material behavior, which requires different material inputs than the implemented linear material behavior of steel materials. The creep of thermoplastic materials in particular ensures that the bolt forces applied are massively reduced and the surface pressure on the seal is significantly reduced. This effect is exacerbated at higher temperatures. The Norton-Bailey approach is used here to predict the creep strain as a function of the applied stresses and time. The model is based on calibration using isochronous stress-strain curves. The reduction in thickness of the flange collars can be calculated using the geometric variables. This is the reason for the bolt force relaxation. The stiffness of the structure represents the relationship between the two variables. The bolt forces in turn are decisive for the surface pressure of the gasket and this is required to determine the leakage class with the corresponding gasket parameters (in accordance with EN 13555). This promising approach is to be validated with the aid of numerical simulations and experimental investigations. Concrete approaches and the test plan will be presented. The AMTEC test rig, which can also be used to determine the gasket characteristics, is suitable. A sandwich structure consisting of a flange collar, loose flange and bolt dummies can be tested there in an upsetting test.

6 Nomenclature

Variable	***Description***	***Unit***
ε_{el}	Elastic strain	[-]
ε_{pl}	Plastic strain	[-]
ε_{cr}	Creep strain	[-]
ε_{ges}	Total strain	[-]
$R_{p0,2}$	Yield strength	[MPa]
Δl	Length change	[mm]
t	Time	[s]
σ_m	Medium stress	[MPa]
σ	Stress	[MPa]
A, n, m	Norton-Bailey parameters	[-]
E	E-Modulus	[MPa]
K, p	Ramberg-Osgood parameters	[-]
F	Force	[N]
$F_{Kl.}$	Remaining clamping force	[N]
F_V	Clamping force	[N]
h	Flange collar thickness	[mm]
b	Flange collar width	[mm]
T	Temperature	[°C]
P_{Rest}	Remaining surface pressure	[MPa]
A_G	Gasket surface	[mm^2]
A_Q	Square ring area	[mm^2]
δ_S	Stiffness screw	[mm/N]
δ_T	Stiffness of thermoplast	[mm/N]
α	Coefficient of thermal expansion	[1/K]

7 Literature references

[1] Amtec Berechnungssoftware: TEMES fl.cal. Lauffen am Neckar. 2023.

[2] Bundesministerium für Umwelt: Technische Anleitung zur Reinhaltung der Luft-TA Luft. 2002.

[3] Deutsche Industrie Norm 1591: Flansche und ihre Verbindung - Regeln für die Auslegung von Flanschverbindungen mit runden Flanschen und Dichtungen. 2014.

[4] Deutsche Industrie Norm 13555: Flansche und ihre Verbindungen – Dichtungskennwerte und Prüfverfahren für die Anwendung der Regeln für die Auslegung von Flanschverbindungen mit runden Flanschen und Dichtungen. 2021.

[5] Funke, D.: Kalibrierung isotroper Materialmodelle für FE-Analysen von thermoplastischen Kunststoffteilen. Präsentation Firma Hengst SE. 2023.

[6] Riedl, A. und Wilming, H.: Harmonisierung der Anforderungen an dichte Verbindungselemente wie Flanschverbindungen zur Begrenzung von diffusen leichtflüchtigen organischen Emissionen (VOC). Umweltbundesamt. 2019.

[7] Kurz, H.: Auslegung und Optimierung vpn Flanschverbindungen mit SMC-Losflanschen und PTFE-Dichtungen. Dissertation. 2014.

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