Stress-strain analysis of hybrid joints using numerical simulation

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Abstract. The design of joints between components of technical structures or equipment is a very important part of the design process and therefore significant attention must be paid to them. However, in certain cases, the values of the stress-strain state in a fixed joint exceed the strength limits, and it is therefore necessary to apply a combination of methods for a permanent joint, the so-called hybrid joint, which will lead to a reduction of evaluated stress-strain values. Problems of stress-strain state of hybrid permanent joints are analysed in this paper. Presented hybrid joint is formed by the combination of the pressed fit connection and fillet weld. The dimensional parameters and material properties each of type of connections are important for these hybrid joints application. Important parameters that affect the stress-strain state for this type of joint are mainly the size of the overlap of the pressed joint and also the geometric parameters of the fillet weld. In the framework of computer simulations and strength analyses are investigated the effects of different size of overlap of pressed fit joint and various design solutions of fillet weld joint on load capacity of hybrid connection under load. The results and some new knowledge resulting from these analyses are applicable in the design of similar types of joints in technical equipment and structures.

1. Introduction
The design of various technical devices and structures for which the functionality and reliability is required is subjected to the application of appropriate calculation procedures and standards [1-2]. Computer simulations and analyses based mainly on the finite element method have a leading position in predicting the stress-strain state that occurs in the proposed structure due to the applied load. The design of mutual connections between components of technical structures or equipment is a very important part of design process and therefore the significant attention must be paid to the connection design.

Generally, the components of structures can be connected by demountable or permanent joints. In order to increase the load-bearing capacity of the permanent joints, a suitable combination of joints based on different physical principles can be used. The hybrid connection presented in this paper is based on combination of press fit connection and fillet weld. The dimensional parameters as well as the material properties of each type of partial joint, used to create the hybrid joints, are important for the practical application of these hybrid joints and for determining their load-bearing capacity. Important parameters that affect the stress-strain state and load-bearing capacity of hybrid connections of these types, are mainly the overlap size of pressed fit connection and also the type and geometrical parameters of the fillet weld. Problems of stress-strain state of permanent hybrid joint are analysed in this paper. In the framework of performed computer simulations and analyses, the effects of different overlap values of pressed fit and various dimensions of fillet weld on load-bearing capacity of hybrid connection under loading are investigated.
2. Structure of permanent hybrid joint

The permanent hybrid joint of structural elements is required which consists of a cylindrical pin and wall (Figure 1). This permanent hybrid joint is created by applying two types of connections, which are based on different physical principles - pressed fit connection and fillet weld. The use of both types of joints does not allow the pin to be pulled out of the hole. It is clear that each of considered connections has certain strength limits. If only the one type of the considered connections is used (i.e., pressed fit connection or fillet weld), at a certain load level $F$, the destruction of the joint occurs. Thus, it can be expected that by simultaneously using both considered types of joint, the load-bearing capacity of the joint will be increased.

The geometry of structure joint and the individual dimensions of the structural elements are shown in Figure 1. The basic dimensions of the permanent hybrid joint are: pin radius $R_0$, flange radius $R_p$, flange thickness $L_p$, pin overlap on both sides of the flange $L_c$, overlap pressed fit connection $\Delta r_0$ and size of fillet weld $a_w$. The basic geometric dimensions, material properties and loads used in numerical simulations are presented in Table 1.

![Figure 1. Structural model of permanent hybrid joint.](image)

| Parameter                          | Symbol | Value  | Unit |
|------------------------------------|--------|--------|------|
| pin radius                         | $R_0$  | 30     | mm   |
| flange radius                      | $R_p$  | 40     | mm   |
| flange thickness                   | $L_p$  | 60     | mm   |
| pin overlap on both sides of the flange | $L_c$ | 7      | mm   |
| size of fillet weld                | $a_w$  | \{3;4;5;6\} | mm |
| overlap pressed fit connection     | $\Delta r_0$ | \{1;3;5;10\} | µm |
| axial force                        | $F$    | 50     | kN   |
| Young modulus                      | $E$    | 210    | GPa  |
| Poisson's number                   | $\mu$  | 0.3    |      |
| density                            | $\rho$ | 7800   | kg.m$^{-3}$ |
| friction coefficient               | $f$    | 0.2    |      |
3. Strength evaluation of fillet weld joint under standard Eurocode 3

The design resistance of a fillet weld shall be determined using the method given in standard Eurocode 3 [1-2]. The resistance of a fillet weld may be assumed to be adequate if, at every point in its length, the resultant of all the forces per unit length transmitted by the weld does not exceed its design resistance.

The resistance of a fillet weld can be considered as satisfactory at each weld point if the resulting stresses transmitted by the weld do not exceed its design resistance expressed as follows:

- for distribution of equivalent (von Mises) stresses $\sigma_{w,eq}$ in the throat section of the fillet weld the fulfil of the following strength limit is assumed

$$\sigma_{w,eq} = \sqrt{\sigma_{\perp}^2 + 3(\sigma_{\perp}^2 + \tau^2)} \leq f_{uw,d}^{(1)} = \frac{f_u}{\beta_w \gamma_{Mw}}$$  \hspace{1cm} (1)

- for distribution of normal stresses $\sigma_{\perp}$ in the throat section of the fillet weld the fulfil of the following strength limit is assumed

$$\sigma_{\perp} \leq f_{uw,d}^{(2)} = \frac{f_u}{\gamma_{Mw}}$$  \hspace{1cm} (2)

- for distribution of maximum shear stresses $\tau_{max}$ in the throat section of the fillet weld the fulfil of the following strength limit is assumed

$$\tau_{max} \leq f_{uw,d}^{(3)} = \frac{f_u}{\beta_w \gamma_{Mw}^{\frac{1}{3}}}$$  \hspace{1cm} (3)

where $f_u$ - is the nominal ultimate tensile strength of the weaker part joined,

$\beta_w$ - is the appropriate correlation factor,

$\gamma_{Mw}$ - is the partial safety factor of welded connections ($\gamma_{Mw} = 1.25$),

$\sigma_{\perp}$ - is the normal stress perpendicular to the throat,

$\tau_{\perp}$ - is the shear stress (in the plane of the throat) perpendicular to the axis of the weld,

$\tau_{||}$ - is the shear stress (in the plane of the throat) parallel to the axis of the weld.

| Type of steel | $f_u$ [MPa] | $\beta_w$ [-] | $f_{uw,d}^{(1)}$ [MPa] | $f_{uw,d}^{(2)}$ [MPa] | $f_{uw,d}^{(3)}$ [MPa] |
|--------------|-------------|--------------|-------------------------|-------------------------|-------------------------|
| S235         | 360         | 0.8          | 360.0                   | 288.0                   | 207.8                   |
| S275         | 390         | 0.8          | 390.0                   | 312.0                   | 225.2                   |
| S355         | 490         | 0.9          | 435.6                   | 392.0                   | 251.5                   |

4. Numerical simulations and results

Computational models and required numerical simulations of permanent hybrid connections are created using the finite element method in the ANSYS program system. Since the geometry of the permanent hybrid joint as well as its loading process satisfies the conditions of axial symmetry, the computational finite element model and numerical simulations will be performed as an axially-symmetric problem. The relationship between the pin outer surface and the inner surface of hole is modelled as a contact problem. The load process is modelled using two load steps.

The first load step represents the creation of a pressed fit connection. To create a pressed fit connection, the thermoelastic analogy is applied using this and the desired overlap size pressed fit is created. The relationship between the overlap value required to create a pressed fit connection and the thermoelastic extension of pin is defined by the following equation
\[
\Delta r_0 = \alpha_{pin} \cdot R_0 \cdot \Delta T \quad \Rightarrow \quad \Delta T = \frac{\Delta r_0}{\alpha_{pin} \cdot R_0}
\]  

where \( \alpha_{pin} \) - is the coefficient of linear thermal expansion,

\( \Delta T \) - is the temperature increment corresponding to \( \Delta R_0 \) is applied into pin component.

The second load step is represented by the procedure of creating and considering the effect of the fillet weld and the subsequent loading of the permanent hybrid joint using the force \( F \) in the axial direction (see Figure 1).

Using the numerical simulations on the model defined above, stress-strain states that result from the considered load cases are investigated and analysed. The numerical simulations performed on the calculation model take into account the relevant dimensional parameters that affect the load-bearing capacity of the hybrid joint and the stress states in the throat of fillet weld.

Overview the results of stress-strain analyses for various parameters (fillet weld dimension, overlap value of pressed fit connection) are graphically presented in the Figures 2 - Figure 7.

**Figure 2.** Dependence of evaluated stresses (\( \sigma_{eq}, \sigma_1, \tau_{xy} \)) in the throat of fillet weld joint  
\((a_w = 3 \text{ mm})\) on overlap value \( \Delta r_0 \) of pressed fit connection.

**Figure 3.** Dependence of evaluated stresses (\( \sigma_{eq}, \sigma_1, \tau_{xy} \)) in the throat of fillet weld joint  
\((a_w = 5 \text{ mm})\) on overlap value \( \Delta r_0 \) of pressed fit connection.
Figure 4. Influence of overlap size pressed fit connection on decrease of relative values of monitored stresses ($\sigma_{eq}, \sigma_1, \tau_{xy}$) ($a_w = 3$ mm) in the throat of fillet weld joint.

Figure 5. Influence of overlap size pressed fit connection on decrease of relative values of monitored stresses ($\sigma_{eq}, \sigma_1, \tau_{xy}$) ($a_w = 5$ mm) in the throat of fillet weld joint.

Figure 6. Influence of overlap size pressed fit connection on decrease of maximum relative values of monitored stresses ($\sigma_{eq}, \sigma_1, \tau_{xy}$) at the root of the fillet weld for various dimensions of fillet weld.
Figure 7. Influence the various dimensions fillet weld on decrease of maximum relative values of monitored stresses ($\sigma_{eq}, \sigma_1, \tau_{xy}$) at the root of the fillet weld for different values of overlap size pressed fit connection.

Conclusions
The permanent hybrid connection, which is a combination of fillet weld joint and press-fit connection is analysed in this paper.

The main results resulting from performed numerical simulations of strength analysis permanent hybrid connection:

- enlarge overlap size for pressed fit connection causes the significant decreasing in the values of equivalent (von Mises) stress $\sigma_{eq},$ first principal stress $\sigma_1$ and also shear stress $\tau_{xy}$ in the throat plane of fillet weld,
- application of press-fit connection in permanent hybrid joint allows to use smaller dimensions of the fillet weld while the required carrying capacity of the hybrid joint is respected.

The results and new knowledge resulting from analyses of permanent hybrid joints, which confirm a significant reduction of evaluated stresses in the fillet weld, are useful and applicable in designing the similar types of joints in technical devices and structures.

References
[1] Eurocode 3: Design of steel structures. Part 1-1: General rules and rules for buildings. STN EN 1993-1-1, 2005.
[2] Eurocode 3: Design of steel structures. Part 1-8: Design of joints. STN EN 1993-1-8, 2005.

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