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A new Design Concept for Point Fixed Glazing

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The determination of load carrying capacity and serviceability of point fixed glazing is a challenging task. A lot of parameters have an influence on the resulting values, especially on stress values around the bore hole. Generally, only specialized engineers are able to perform this analysis. Reasons for this are the multitude of parameters, the lack of analytical solutions and incompletely analyzed load carrying mechanisms on the one hand, and on the other hand, the lack of a generally accepted and accurate design concept for stress and deflection calculation in Germany. The calculation of point fixed glazing is usually done by using finite element analysis (FEA). However, the scatter of the results is very large – which means that the quality can be evaluated as low. The reasons for these deviations are usually based on the deficient FEA software and an inaccurate modeling done by the user. Therefore, the user needs a guideline for the design process. A new design concept for point fixed glazing has been developed on the basis of analytical, experimental and numerical studies. This new concept consists of two main parts. The first part is a quality check of the calculation model. The user has to prove his model by reference values and theoretical principles. The second part deals with the actual calculation process of the whole glazing. This process has to be done as case-specific analysis. Thereby, it contributes to a safe and realistic design process in the field of point fixed glazing.

Keywords: point fixed glazing, design concept, stress concentration

1. Motivation

Nowadays point supported glazing with drilled holes seem to be standard. Nevertheless, the design process is a challenging task for the users as well as the software manufacturers. Reasons for this are the multitude of parameters, the lack of analytical solutions and incompletely analyzed load carrying mechanisms on the one hand, and on the other hand, the lack of a generally accepted and accurate design concept for stress and deflection calculation in Germany. Apart from one simplified design method, there is no general design method for point fixed glasses in the established technical regulations at present.

The determination of load carrying capacity and serviceability of point fixed glazing is sophisticated, if the results should be close to reality. A manual calculation of the decisive values for design (deflection and stress) is not possible in contrast to linear supported structures. The necessary calculations are usually performed by using finite element software. The use of such software tools is no guarantee of correct results. The results depend on the applied software and the modeling by the user. Insufficient models or a neglect of parameters can lead to strong deviations in the results (FKG 2006; Seel and Siebert 2014). The results can exhibit variations which do not meet the requirements for safety or economy. Therefore, the user needs a guideline for the design process of point fixed glazing.

Based on analytical, experimental and numerical studies a design concept for point fixed glazing is presented in this paper. It can serve as a guideline for the design process of such constructions. The focus is on point fixed glass plates with cylindrical holes (see Figure 1). This contribution is an English version of Seel and Siebert (2016). Further details and background information are listed in Seel (2015).

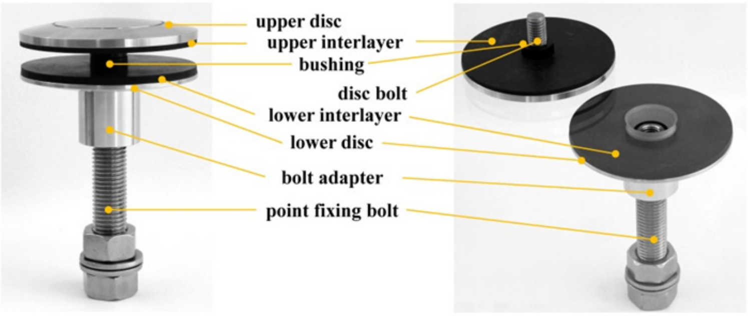

Fig. 1 Typical point fixing (2015).

2. Existing design methods

The design of point supported glazing was investigated in a multitude of publications (e.g. Albrecht 2004; AiF 2012; Beyer 2007a; Siebert 2004). As a result, four detailed and one simplified design method (SLG) were developed. The simplified method is a user-friendly method without extensive FE-models with bore holes, contact approaches and protracted quality checks. The disadvantages are limitations in fixing and bore hole geometry. In contrast, there are four detailed design methods (DM) which are summarized in Table 1 with their single examining steps. Through these procedures the users must prove with the help of a gradual testing method that her models are suitable for the actual design process. The required steps can be seen in Table 1. Partly different approaches come into operation for the existing methods. Two methods demand control of the mesh modeling (mesh verification). This important step is also recommended in DIN 18008-3 (2013). The model adjustment and accordingly the quality check of modeling take place through all methods, either by spring stiffness or by strain distributions. The required reference values are provided by the manufactures or are determined experimentally. Finally, a calculation of a whole four point fixed glazing is required in two design procedures. The evaluation of the whole structure (incl. point fixing) is done by comparative values (support reactions, stress and deflection). In AiF (2012) the design methods DM 1 to DM 3 are analyzed concerning user-friendliness, practicability, security and reproducibility. None of the methods fulfill all requirements in a satisfactory way. The design method DM 4 was developed from some components of DM 1 to DM 3, in which the benefits were combined. With all procedures (incl. DM 4) the collection of experimental data requires a lot of experience and accuracy. For example, the determination of the strain distributions in the drilling area turns out as very extensive and fault-prone. The use of such reference values for a quality check with an allowed tolerance range of ± 5% is critical. A model adjustment on the basis of an experimental spring stiffness, which depends on viscoelastic and hyperelastic material behavior of the interlayers as well as on friction in the point fixing area, could be problematic. On the one hand, the measured stiffness values extent in a wide region (AiF 2012; Seel 2015) and, one the other hand, all spring stiffness influencing parameters must be familiar and considered in a FE-model. Experimental and numerical investigations in Seel (2015) show that the spring stiffness is a non-constant value as is conditioned by the friction based lateral strain restraint in the contact area of the interlayer. Without consideration of friction effects and other spring stiffness influencing parameters (e. g. preload force) the target stiffness (experimental data) is easy to adjust by selecting the Young's modulus of the interlayer. However, this approach leads to a mixture of various factors. Nevertheless, these factors may affect the design relevant values in different ways.

Table 1: Overview of the detailed methods (incl. examining steps)

Examining steps	Design method (DM)			
	DM 1 (Brendler and Schneider 2004)	DM 2 (Siebert 2006)	DM 3 (Kasper 2006)	DM 4 (AiF 2012)
Evaluation of mesh quality around a hole	no	yes	no	yes
Evaluation of point fixing model	spring stiffness	strain distribution	strain distribution	spring stiffness
Evaluation of whole glazing	yes	no	no	yes

3. New design concept

3.1. General

In this chapter, a new design concept for the analysis of point fixed glazing is presented. The concept is based on analytical, experimental and numerical studies and consists of two main parts. The first one is a gradual quality check of the calculation model. The user has to scrutinize the model to check if it is suited for further calculations. If the model passes the quality check, the actual calculation process of the whole glazing can be carried out in the second part of the design concept. All relevant design scenarios are taken into account during the second part. Details and background information to this new concept are listed in Seel (2015).

3.2. Quality check of the modeling

The quality of the modeling has to be checked by a step by step procedure. Figure 2 gives an overview of the procedure. The process of the quality check is divided into three steps. The last step is subdivided into three sub-steps itself. The individual steps have to be executed, in a sequence. Each examining step has to be successfully fulfilled. The modeling of the previous one is needed for the following step. If the requirements for an examining step are not completed, the model has to be changed to a suitable form. The restrictive calculations are performed on small-sized models. The data of the small-sized models are based on the prospective components (point fixing and glazing). The evaluation of the used modeling variants is carried out with the help of contact stress and principal stress values. Recognized equations, developed solutions and theoretical principles are used as reference values. Under consideration of the manufacturer's specification, sensible values have to be chosen if the dimensions of the components are still unknown. The final dimensions have to be determined by an iterative procedure. In principle, the gradual procedure is a useful tool to exclude inadequate models.

In the following, the individual steps with the necessary requirements are described.

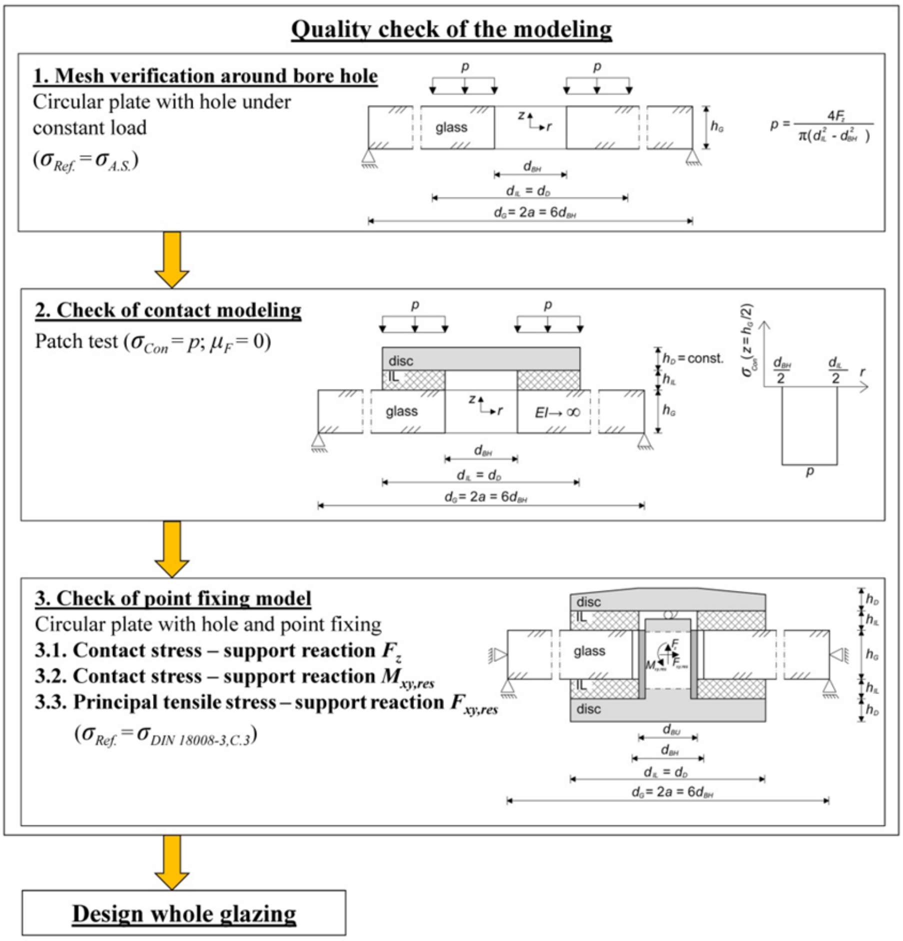

Fig. 2 Quality check of the modeling (overview) in accordance with Seel (2015).

3.2.1. Mesh verification around the bore hole

The structural system (circular plate with center hole) and the rotationally symmetric load *p* are illustrated in Figure 3. The geometry data of the plate depend on plate thickness h_G and hole diameter d_{BH} of the prospective glazing. Bevels in the drilling area of glazing are not taken into account. The diameter of the circular plate with hole is calculated by the six-fold bore diameter in accordance with Beyer 2007a. The circular plate is simply supported in z-direction at the external circle. The material data of glass have to be used. The load area corresponds to the contact area between glass and interlayer. Generally, the load area is defined by the hole's diameter in the inner region and in the outer region by diameter of disc d_D or rather interlayer d_{IL}. The value of the uniform load *p* depends on the support load F_z (e. g. 1 kN) and the load transfer area. The calculation of *p* is given by:

$$p = \frac{4 \cdot F_z}{\pi \left(d_{IL}^2 - d_{BH}^2\right)}. \tag{1}$$

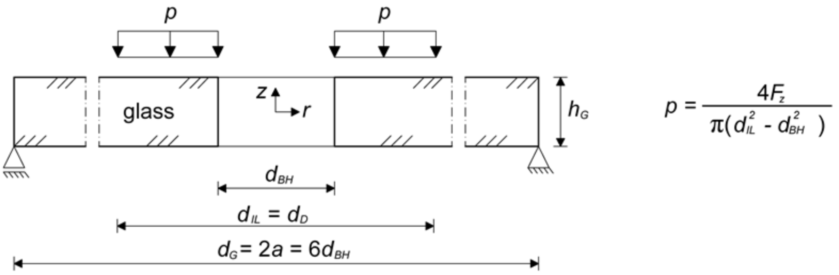

Fig. 3 Mesh verification around the bore hole in accordance with Seel (2015).

The quality of the meshing in the bore hole area is evaluated with the help of the maximum principal stress values. The reference solution $\sigma_{Ref.}$ is an analytical one ($\sigma_{A.S.}$) for a circular plate with hole (Seel and Siebert 2012), which is based on Kirchhoff's plate theory. The detailed derivation of the analytical solution can be found in Seel 2015 as well as in Seel and Siebert 2012. It has to be mentioned that a reference solution $\sigma_{Ref.}$ of the present geometry must to be appointed for each case. The calculation of the reference solution $\sigma_{Ref.}$ can be done with an Excel-based software tool (Seel et al. 2012). This tool is freely available for download. A tolerable deviation of results from the reference solution is +/- 5% in accordance with DIN 18008-3 (2013). In case of a failed or intolerable result the meshing should be adapted to a sufficient modeling (Siebert 2004).

3.2.2. Check of the contact modeling

The evaluation of the contact modeling occurs by the contact stress distributions between glazing and interlayer. For this step the identical circle plate from the previous step is used. Complementary to the glazing the interlayer and the disc must be considered in the model as it can be seen in Figure 4. The two additional elements need to widely conform to the actual properties of the point fixing regarding the geometry conditions in Figure 4. Haunches and holes of the disc are disregarded. The surface load *p* from the previous step needs to be placed on the disc (see Figure 4). The material values of the different components have to be used. Merely friction effects are to be neglected. Furthermore, a flexural rigid glazing must be examined ($E_G \rightarrow \infty$). In case of using an interlayer without defined material values (e. g. elastomer), the limiting values of the Young´s modulus (5 and 200 N/mm^2) mentioned in DIN 18008-3 (2013) must be utilized. On the contrary to DIN 18008-3 (2013) ($\nu = 0.45$), a Poisson´s ratio for elastomer of 0.49 is recommended due to the incompressibility of elastomer like EPDM.

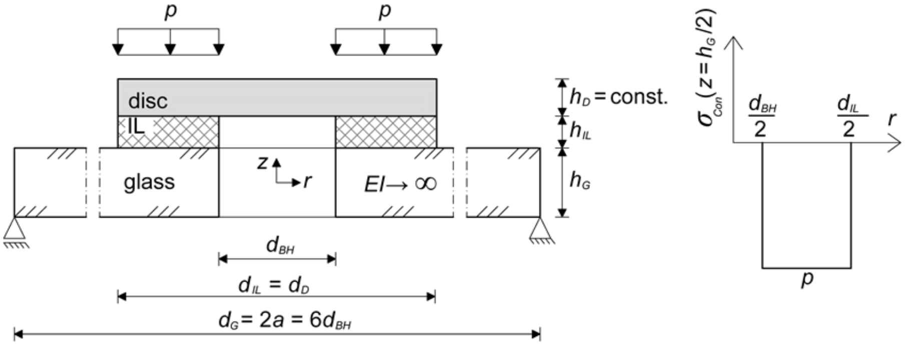

Fig. 4 Check of the contact modeling in accordance with Seel (2015).

As a criterion for a suitable contact modeling (Figure 4) and according to El-Abbasi and Bathe (2001) and Taylor and Papadopoulos (1991) it is demanded, that the contact stress σ_{Con} between the glazing and the interlayer should corresponds approximately to the surface load *p.* In ideal case, a constant contact stress distribution exists as a result of the flexural rigid glazing. Insufficient modeling variants point out unstable or oscillatory contact tension distributions. Parable-shaped distributions are also not allowed. Such distributions are hints for stiffening effects, which generally lead back to friction effects or rigid connection between single contact elements (disc – interlayer – glazing). Load transfer by tension is also not allowed. Merely in the edge areas deviations from the reference are accepted. Reasonable for this is that large lateral deformations arise especially for interlayer with low Young´s modulus values in combination with large Poisson´s ratio. Some adequate and inadequate models are listed in Seel (2015).

3.2.3. Check of the point fixing model

This step is subdivided, accordingly of the support reactions in the point fixing area, into three sub-steps. The three support reactions are the force F_z normal to the plane, the resulting force $F_{xy,res}$ in plane and the resulting moment $M_{xy,res}$ (Figure 5). The point fixing modeling has to be checked by contact stress distributions or maximum principal tensile stress. In contrast to the previous step the real point fixing with the geometry and material data of each single component is to be used. Note that in this step the actual Young´s modulus of the glazing needs to be applied (70000 N/mm^2). Only the friction effects are not taken into account. If the material values for the interlayers and the bushing material are not given the limiting values, referred to DIN 18008-3 (2013), have to be utilized. Existing haunches, hinges and other details need to be considered in a model. The middle plane is the origin of all support reactions as it can be seen in Figure 4. The circular plate is supported at the external edge in vertical and radial direction. The structural system and the matching dimensions are illustrated for this three-part step in Figure 5.

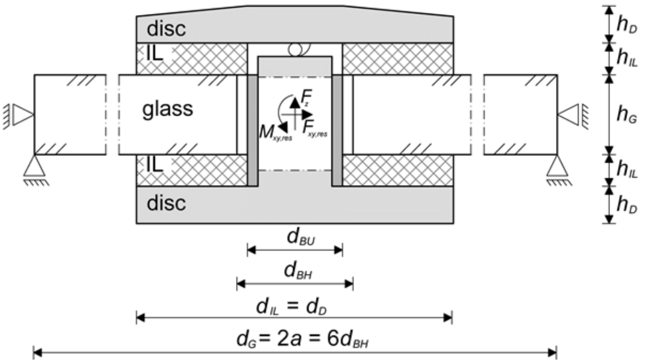

Fig. 5 Check of the point fixing model in accordance with Seel (2015).

3.2.3.1. Support reaction F_z and $M_{xy,res}$

In this section, the steps for support reaction F_z and the moment $M_{xy,res}$ are summarized, due to the fact that the criteria of evaluation are the same. Each step needs to be carried out separately. Both support reactions are transferred mainly by contact stress between glass, interlayer and discs. Nevertheless, in the area of the drilling edge additional contact stress can appear, in particular with close-tolerance connection and under acting moment $M_{xy,res}$. A value of 1 kN for the support reaction F_z and 25 Nm for the moment $M_{xy,res}$ are recommended for the calculations. The evaluation of the point fixing model is executed with the help of resulting contact stress values between glazing and interlayer and accordingly bushing. Also the component and element deformations are to be checked for inadequacy. The criteria for both steps are:

- exclusive load transfer by contact pressure,
- adequate distribution of the contact stress considering the support reactions and the deformation figure,
- steady distribution of the contact stress by existing contact,
- no general penetration of contact bodies and
- no strongly distorted elements (except boundary elements).

Examples of suitable and unsuitable contact modeling variants are listed in Seel (2015).

3.2.3.2. Support reaction $F_{xy,res}$

In contrast to the evaluation criteria of the previous section (3.2.3.1), the maximum principal stress in the glazing is evaluated comparatively. The numerical result is compared with a reference solution following Eq. (C.3) in DIN 18008-3 (2013). Each reference value $\sigma_{Ref.}$ can be calculated in dependence on the stress component factor b_{Fres}, the reference thickness t_{ref} (10 mm), drilling diameter d_{BH} and the support reaction $F_{xy,res}$ by Eq. (2).

$$\sigma_{Ref.} = \frac{b_{Fres} \cdot h_{ref}}{d_{BH}^2 \cdot h_G} \cdot F_{xy,res} \tag{2}$$

The stress component factor b_{Fres} in Eq. (2) is listed in table C.2 (DIN 18008-3 2013). A value of 1 kN is recommended for the support reaction. Eq. (2) is valid for fixed combinations of Young ´s modulus of the bushing E_H and a gap between the drilling edge and the bushing t_{Gap}. For instance, Eq. (2) can be used for the combination $E_H \geq 3000$ N/mm^2 and $t_{Gap} \geq 1$ mm. Reference values for close-tolerance connection ($t_{Gap} = 0$ mm) can be found in the literature (e. g. AiF 2012; Maniatis 2006). As a criterion for a successful passing of the last step it is suggested that the results of the numerical simulation should differ in maximum ± 5 % from the reference value.

3.3. Design proposal

As a result of the material behavior of the elastomeric interlayers, the amount of parameters and their partial different influences, the design proposal are mainly based on case specific investigations. The general aim is to take all relevant design scenarios into consideration. To fulfill the evidence of load carrying capacity (ULS) and serviceability (SLS) the maximum design values of action effects (principle stress and deflection), which result from several scenarios and accordingly from the parameter combinations, have to be less or equal than the design values of resistances (R_d / C_d). The following parameters are to be noticed or varied between fixed limitations:

Fixing geometry and specification
In the model, the real geometry data and possible hinge effects between single fixing components must be considered.

Load direction
Users have to pay attention on the load direction (e. g. wind pressure and suction) by the application of asymmetrical fixings (reference plate middle layer).

Friction effects
A general neglect of friction effects does not correspond to the safety standards in point fixed glazing (Seel 2015; Seel and Siebert 2015). Frictional effects can be implemented by friction laws and the matching coefficients. These situations have to be considered:

- design without friction,
- design with minimum friction values (e. g. friction coefficient) and
- design with maximum friction values (e. g. friction coefficient).

The effects of friction can be considered indirectly by an additional partial safety factor γ_{Fr}.

Preload force in the point fixing
By tightening the disc bolt of a point fixing with a torque, the connection glass - point fixing is pre-stressed. The induced preload force F_{PF} leads to a stiffer connection between glass and fixing and to a stiffer system behavior of the whole construction. Larger principal stress values appear due to the stiffer system behavior, especially in case of four point fixed glazing (Seel 2015; Seel and Siebert 2014). For a calculation the following limiting cases are mentioned:

- design without preload force and
- design with maximum preload force (one day after installation).

The direct implementation of the preload force in the model turns out to be time-consuming. An indirect consideration of the preload force can also be realized through an additional partial safety factor γ_{PF}.

Material behavior and material data
Generally, it is sufficiently to perform the linear elastic analysis. Not to neglect the distinctive viscoelastic and hyperelastic material behavior of the interlayers (e. g. EPDM), the calculations must be carried out with the minimum and maximum Young's modulus of the interlayers. The following cases have to be considered:

- design with minimum Young's modulus (elastomer e. g. 5 N/mm^2 in DIN 18008-3 2013) and
- design with maximum Young's modulus (elastomer e. g. 200 N/mm^2 in DIN 18008-3 2013).

Installation situation
In case of a gap between the hole's edge and the bushing, the following situations have to be examined:

- centric installation (no contact in installation state) and
- non-centric installation (contact in installation and load state).

The listed influencing factors or rather limit cases can be complemented with additional aspects. A reduction is also possible, if the respective parameters are "exactly" known and constant over the utilization time. Single parameters like friction coefficients or preload forces, can be found in the literature (e. g. Seel 2015; Ebert 2014) or in the manufacturer's data. Missing values must be determined by experimental investigations.

Due to the described aspects, up to 24 different design scenarios can occur in the case of ultimate limit state (ULS), although a stiffer system behavior leads generally to higher tensile stress values around the bore hole (four point fixed glazing). In contrast to the support region, a low system stiffness is relevant for maximum design values in the field region. Also for a standard six point fixed glazing the maximum stress value arise due to a low system stiffness.

In general, the system stiffness rises with the increase of the parameters Young's modulus (interlayer), friction coefficient and preload force. The described principles are not always appropriate. Therefore, it is essential to observe different scenarios. The design relevant deflections (serviceability limit state) are generally based on a low system stiffness. This leads to a reduction of the design situations in case of serviceability. The required evidence for the fixings can be done on the base of technical approvals or with the help of the "test instruction point fixing" (see attachment D of DIN 18008-3 2013).

The application of partial safety factor represents an easy and user-friendly possibility to consider the effects of friction and preload force in the calculation and to reduce the effort in general. In order to simplify, it is recommended that the partial safety factor γ_{Fr} and γ_{PF} should be implemented on the "action effect side" (E_d). The stress values in the point fixing area are to be multiplied by the partial safety factors if the point fixing model without friction and preload force occurs. Based on parameter studies at four point fixed glazing, the following partial safety factors are determined. The partial safety factors for friction amounts in maximum 1.38 and the maximum value for the indirect consideration of the preload force is 1.22. For six point fixed glazing the values are below the prior ones. This calculation proposal and the given values are based on investigations of four and six point fixed glazing with symmetric arrangement of point fixings.

The first part of the presented procedure (quality check of the modeling) should be extended by one additional step (friction modeling). For a consideration further investigations in the field of friction are necessary in addition to existing studies (e. g. Maniatis 2006; Techen 1997).

4. Special features compared with DIN 18008 and existing methods

In comparison to the existing methods (see Chapter 2) the presented method differs in the fact that the evaluation of the modeling does not occur on the basis of extensive experimental data. The quality check of the models is performed by the help of contact stress distributions and principal stress values. The respective reference and comparative values arise from approved equations, analytical solutions and theoretical principles. In comparison to the procedures DM 2 (Siebert 2006) and DM 4 (AiF 2012) the reference solution of the mesh verification around the bore hole shows a mechanical origin. In the mentioned design procedures (DM 2 and DM 4) as well as in DIN 18008-3 (2013) the used reference solution (Roark 1976) represents only an experimental based approximate solution, which is, with priority, valid for materials with Poisson´s ratio of 0.3.

Beside the kind of point fixing modeling, a large number of influencing factors have an impact on relevant values in different ways. Therefore, a limitation of the parameter space is recommended. A practicable manner is an exclusion of favorable factors. For instance, it is assumed that the effects of friction and preload force in the point fixing area have a stress reducing influence. In general, these effects are not considered. The numerical investigations in Seel (2015) and Seel and Siebert (2014) found out that relevant values are mainly influenced by the often disregarded parameters friction and preload force. The consideration of these parameters leads in case of a four point fixing up to 45 % higher stress values in comparison to practical models (without friction and preload force). However, an increase of friction and preload force causes a reduction of stress and deformation values in the middle of the plate (field region). In contrast, for a six point fixing the maximum stress values appear in the point fixing area mainly for the instance without friction and preload force. The implementations point out that both factors can cause stress increasing as well as stress decreasing. Another example of a divergent effect is the value of the Young´s modulus of the interlayer. For a four point fixing, including a single-layer glazing, high values of the interlayer (200 N/mm^2) result in maximum stress values. The usage of a laminated glazing with relatively low shear stiffness of the composite film leads to a maximum stress value, if the Young´s modulus of the interlayer amounts 5 N/mm^2.

With the help of the performed examples, it becomes evident that a disregard of "favorable parameters" does not always represent a conservative approach for design. As a result of the complexity and the partial different parameter influences, the users are strongly advised to pay attention to the various design scenarios, which can provoke relevant design values. Thus, the investigation of different limiting cases is necessary and an important part of the design proposal (see chapter 3.3). Therefore, this approach is a unique feature towards the common design methods (DM 1 to DM 4).

The exemplary evaluation of whole glazing (four point fixed) does not occur in this presented method. In the view of the complexity and the inconsistent parameter effects it is essential to consider the different design scenarios. Regarding the total structure, the warranty of the design relevant results, which represent the "safe side", is more reliable with this method as on the basis of comparative calculations.

5. Summary and outlook

Within the scope of this contribution a detailed design procedure was introduced for point fixed glazing. It can be used as a guideline for the design process. After a gradual modeling control different calculation situations are to be examined by the users, if necessary with suitable software support, so that the decisive design values can be included. A universally valid forecast of the leading design situation is difficult due to the amount of parameters and their partly different effects. Since of many design situations are to be analyzed, the use of the developed and case-specific based design procedure should be easier for the users. A possible approach would be the development of a software tool which executes the various situations internally. Such a tool would lead on the one hand to a safe calculation of point fixed constructions and, on the other hand, to an acceptance increase of the procedure.

To sum up, the determination of load carrying capacity and serviceability of point fixed glazing is and will remain a challenge for the users as well as the software manufacturers. Nevertheless, this paper contributes to a safe, comprehensible and economic design process in the field of point fixed glazing.

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