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ROBUSTNESS IN CIVIL ENGINEERING - INFLUENCES OF THE STRUCTURAL MODEL ON THE EVALUATION OF STRUCTURAL ROBUSTNESS

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Abstract. *The topic of structural robustness is covered extensively in current literature in structural engineering. A few evaluation methods already exist. Since these methods are based on different evaluation approaches, the comparison is difficult. But all the approaches have one in common, they need a structural model which represents the structure to be evaluated. As the structural model is the basis of the robustness evaluation, there is the question if the quality of the chosen structural model is influencing the estimation of the structural robustness index.*

This paper shows what robustness in structural engineering means and gives an overview of existing assessment methods. One is the reliability based robustness index, which uses the reliability indices of a intact and a damaged structure. The second one is the risk based robustness index, which estimates the structural robustness by the usage of direct and indirect risk. The paper describes how these approaches for the evaluation of structural robustness works and which parameters will be used. Since both approaches needs a structural model for the estimation of the structural behavior and the probability of failure, it is necessary to think about the quality of the chosen structural model. Nevertheless, the chosen model has to represent the structure, the input factors and reflect the damages which occur. On the example of two different model qualities, it will be shown, that the model choice is really influencing the quality of the robustness index.

1 INTRODUCTION

A large amount of design parameters exist in structural engineering, which have to be taken into account during the design process. A very crucial, but sometimes neglected design parameter is the structural robustness. However, a number of structural collapses in the past [1] have led to a growing importance of this topic. Therefore the topic of structural robustness has been increasingly addressed in literature in recent years. Such that the discussions regarding the development of a practical measurement for the determination of structural robustness have already started. Several approaches for the evaluation of the structural robustness were developed and already exist [2].

The evaluation approaches are based on the probability of failure according to a given input scenario. So it is necessary to evaluate the structural behavior. The basis for this is a structural model, which has to represent all significant input factors. That means it must be able to represent the structural system as well as the influencing loads. For the evaluation of robustness it is necessary that damage in the structural system occurs. That being the case, the structural model must also be able to reflect damage. This shows that the right choice of the structural model highly influences the evaluation process for the structural robustness.

Also, the Eurocodes addresses the topic of structural robustness in DIN-EN 1990 [3] and DIN-EN 1991-1-7 [4]. An overview and also some additional background information are given in [5]. This shows that the topic of structural robustness is gaining more and more attention. Therefore, it is essential to consider the quality of the existing approaches and the influences of the used structural models.

2 THE TERM ROBUSTNESS

2.1 Robustness in other disciplines

The word robust originated from the Latin word *rōbustus*, which means *hard, resistant, strength*. The word robustness is often used in the field of science and describes the property of an object or activity. But as shown in table 1, the meaning of the word robustness sometimes differs.

In technical disciplines, robustness is a sign of high quality. Thus, for example, robust machines can work without any problems under a substantial number of difficult conditions. A partial overload or short-term incorrect use does not lead to damages [6]. That means, an increase of robustness are always equated with an increase in product quality. Therefore, the goal of a more robust product is clearly comprehensible and can be implemented effectively.

2.2 Robustness in structural engineering

In structural engineering, the definition of robustness is not so transparent like in technical disciplines. Because of that, there are some cases where wrong definitions of the term structural robustness exist. The common definition of robustness in structural engineering is related to the behavior of a structure, to resist an occurred input scenario, which temporarily exceeds the limit state of the structure. Thereby, a part of the structural system directly fails by reaching the load bearing capacity. But the rest of the structure has to be stable and rearrange the loads in such a way that no further structural elements fails. This means that the average of damage has to be proportional to the resulting input scenario [7]. Another scenario which has to be considered

Table 1: Different disciplines - Different definitions of robustness [8]

Discipline	Definition
Structural Standards	The consequences of structural failure are not disproportional to the effect causing the failure...
Software Engineering	The ability...to react appropriately to abnormal circumstances (i.e., circumstances ”‘outside of specifications”’). A system may be correct without being robust...
Product Development	The measure of the capacity of a production process to remain unaffected by small but deliberate variations of internal parameters so as to provide an indication of the reliability during normal use...
Statistics	A robust statistical technique is insensitive against small deviations in the assumptions...
Design Optimization	A robust solution in an optimization problem is one that has the best performance under its worst case...

for a robust structure, is the ability of the structure to compensate for deviations between the designed model and the created structure. Since human errors during the building process are sometimes not negligible, the structure needs to be stable against variations in the execution. Also, human errors can occur during the design process. However, since the topic of human errors in structural engineering is expansive, it will not be further addressed in this paper. For further information, there is an ample amount of available literature (e.g. [9] to [12]).

The requirements for structural robustness are sometimes implicitly integrated in the existing codes and design methods, without using the word robustness. Thus, the structural engineer is sometimes more connected with the subject of robustness than he/she is aware of. One example is the design of redundant structures. By the design of more support conditions than necessary, the system includes unused bearing capacities, which can be exhausted in the case of local damage (formation of plastic hinges). Another example is the structural design of a Gerber girder. The arrangement of the hinges has to be in such a way, that the failure of one part of the girder does not lead to a collapse of the overall system.

There are also structural properties which really have to be separated from the topic of structural robustness. The requirement that a structural system has to announce a failure or collapse with high deformations or by the formation of cracks is not related to the term robustness. This is only the request on ductility. Ductility also includes the usage of non-brittle materials. An example, where non-existing ductility leads to a structural collapse is the progressive collapse of power line towers in Westphalia in the year 2005. Due to the structures being more than 50 years old, the codes in existence at this time did not consider the topic of ductility - the structures were constructed with converter steel [7]. Today this type of steel is not allowed in structural engineering, since the problems of ductility and sensitivity to aging is common knowledge nowadays.

2.3 Non-robust structures

History has shown that there were several structural collapses in the past, which could be related to non-robust structures. This means that the consequences of damage were extensively higher than the original causes. One of the most famous structural failures according to a less robust structure is the "'Ronan Point Disaster"' in 1968 in East London [13]. Due to a small explosion in one of the upper floors, a section of the building completely collapses, shown in figure 1. The insufficient design of a connection point, which was not resistant against horizontal loads led to this disaster. Another example for a collapse of a structure related to a non-robust system is the collapse of the exhibition hall in Katowice (Poland) in the year 2006 [14]. The structural system consisted of a very light weight construction and an overload of only 20 % of snow led to the total collapse.

Figure 1: Progressive collapse of the Ronan Point Tower [7]

By considering the topic of structural robustness, it is important to have in mind that robust structures also cannot resist each input action. The design according to the actual standards leads to a bearing capacity dimensioning of each structural member and connection point regarding the given design loads, such that the structure is also robust against this loads. Thus, it is essential to note that an increasing of the assumed loads, an extraordinary load or a pre-damage in the structure leads to a decreasing of the structural robustness and thus to an increase in the probability of failure. The existing approaches for structural robustness uses these differences in the probability of failure to quantify the structural robustness of a system. An overview for different evaluation approaches is given in section 3.

As it is not feasible to check and establish the structural robustness for all potential loads and load histories in the lifetime of a structure, as well as all variations in the execution during the building process, it is necessary to think about the right choice of lifetime scenarios. In any case, the fact that with increasing robustness against several factors or scenarios the structure is also more and more expensive has to be considered.

3 QUANTIFICATION OF STRUCTURAL ROBUSTNESS

The quantification of structural robustness is one of the aspiring topics in structural engineering in the last years. The new Eurocodes addresses the topic and require, that structures have to be robust. This means that the structure has to react in such a way that the overall damage does not extend disproportionately to the original cause [3]. Thus, if an input scenario occurs and a part of the structural system exceeds the limit state and fails, the rest of the system must be able to be stable on its own. Since this declaration is not very comprehensible, different approaches for the evaluation of the structural robustness were developed. Two of them are the reliability based robustness index, which is described in section 3.1 and the risk based robustness index, which is shown in section 3.2. Other approaches are also available in the literature.

3.1 Reliability based robustness index

According to the fact that the probability of failure of a structural system changes with every modification of the loads or any damage scenario, it is possible to evaluate the structural robustness with the help of the system reliability index β, according to the approach of Frangopol and Curly [15]. The reliability index β is defined in equation 1, where Φ is the normal distribution function with $\overline{X} = 0$ and $\sigma = 1$ and P_f is the probability of failure of the considered system. In the safety concepts of structural engineering the reliability index β is strongly embedded, since the determination of the reliability level of a structure is already done by the reliability index β.

$$\beta = -\Phi^{-1}(P_f) \tag{1}$$

The reliability based robustness index by Frangopol and Curly [15], which is defined in equation 2, is based on two different reliability indices. The reliability of the intact structure, with normal design loads and without any damage is described by β_{intact}. Wherein $\beta_{damaged}$ is describing the reliability of the damaged system, which reaches the load bearing capacity by an extraordinary input scenario.

$$I_{Rob} = \frac{\beta_{damaged}}{\beta_{intact}} \tag{2}$$

The defined robustness index I_{Rob} could take values between zero and one, if both reliability indices are positive values. If the probability of failure from one of the systems is higher than 50 %, the robustness index becomes negative. In that case, the robustness is very low, since a robustness of one indicates the best robustness. That means if the robustness index of a structural system is one, there would be no change in the probability of failure after some damage has occurred.

The estimation of the probability of failure could be done by stochastic modeling and the usage of structural reliability methods according to the probabilistic model code [16].

3.2 Risk based robustness index

Another approach for the evaluation of the robustness of a structural system, is the risk based robustness index. This approach was developed by Baker *et al.* [17] and uses the ratio between direct and indirect risk for a predefined load or lifetime scenario. Since there is the possibility of different outcomes by one input scenario, they added an event tree, which includes the different model responses. An example of this event tree is shown in figure 2.

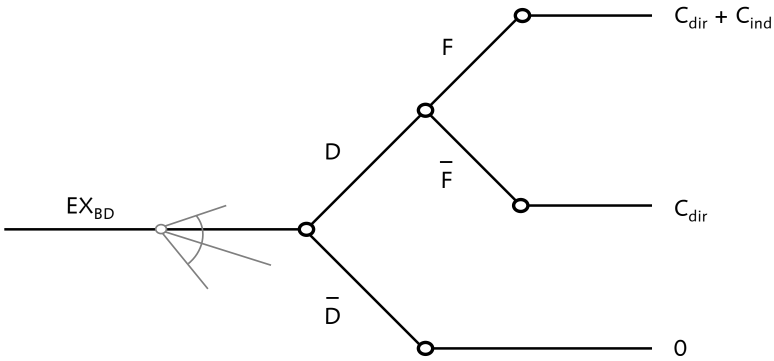

Figure 2: An event tree for robustness quantification [17]

The initial situation for the evaluation of the structural robustness is given by a structural model. This model describes the structural system and must be able to represents all the failure mechanisms and load or damage scenarios. By adding the first exposure EX_{BD}, the system has the potential to react in two different ways. The best way is, that the system is picking up the load without any damage, which leads to path $\overline{D}$ and no consequences appears. If the load is too high and some damage occurs, the system is following path D. The consequences arising from this damage, may be direct (C_{dir}) or indirect (C_{ind}). Direct consequences are those that result explicitly from the first exposure. In this case, damage occurs and one or more structural members fails. Afterwards the load rearranges to other structural members and the new system works independently. If damage occurs and the new system is not able to pick up all the rearranged loads and new damage occurs, it will be described by C_{ind} as indirect consequences. It is also possible, that in this way the whole structure fails. As a result, the consequences increase to a maximum.

Since the robustness index in the approach of Baker *et al.* [17] is defined by the ratio of direct and overall risk, as shown in equation 5, it is necessary to determine the risk of the structure. The term risk is defined as the effect of uncertainty on objectives [18], which means that in the context of structural engineering, risk is the probability of failure of a predefined input scenario multiplied with the consequences of this event [19]. In the case of the event tree shown, the direct risk could therefore be described by equation 3 and the indirect risk can be estimated by equation 4.

$$R_{Dir} = \int_x \int_y C_{Dir}\, f_{D|EX_{BD}}(y|x)\, f_{EX_{BD}}(x)\; dy\; dx \tag{3}$$

$$R_{Ind} = \int_x \int_y C_{Ind} P(F|D = y) \, f_{D|EX_{BD}}(y|x) \, f_{EX_{BD}}(x) \, dy \, dx \tag{4}$$

The robustness index I_{Rob} as shown here can assume values between zero and one, where one indicates a structure without any indirect risk. This means one indicates the highest robustness, where no additional failure occurs. To make this a little bit clearer, there is an application of this risk based robustness evaluation in section 5.

$$I_{Rob} = \frac{R_{Dir}}{R_{Dir} + R_{Ind}} \tag{5}$$

4 STRUCTURAL MODELS

A high number of partial models are already in existence in structural engineering. These could be used to model and evaluate the structural behavior or the load bearing capacity of a structural system. Therefore it is necessary, to really think about the right choice of models which will be used during the design process. Each design goal and every influencing parameter has to be implemented in the used model. This could be done by the usage of an overall, global model, or by coupling of several partial models. This means that in each case there is an increase of model complexity.

One way to choose the models for the design process is by selection based on the experience of the engineer. However, this is not very credible. Another way is the evaluation of the prognosis quality of different coupled partial models. An approach for this was developed by Reuter [20] within Research Training Group 1462 at Bauhaus-Universität Weimar. By coupling of different partial models, it is possible to evaluate the quality of the overall model answer. In this way it is possible to create the best model combination for each output value. The evaluation of coupled partial model by using graph theory was done by Keitel *et al.* [21]. Since both model assessment methods are very practicable to evaluate the best model combination, it would be a promising approach to couple the model evaluation and the estimation of structural robustness.

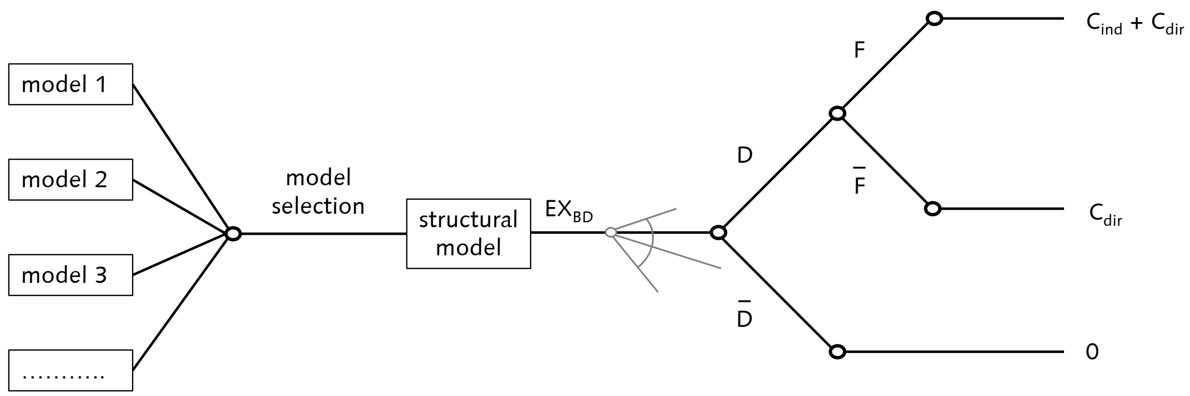

Figure 3: Expanded event tree for model choice and robustness quantification

As mentioned before, there are several approaches to evaluate the robustness of structural systems. One of these is the risk based robustness index, which is described in section 3.2. As recommended in section 3.2, the evaluation will be done by the estimation of direct and indirect risk. To that effect, there was shown an event tree, which is necessary in order to identify the different model outcomes. As also mentioned before, there are no limitations or quality checks for the structural models which will be used to reflect the structure. Shown in figure 3 is a scenario how this event tree expands if the model choice or model evaluation is added.

The different input models could be different partial models, which have to be combined to a global model. But also global models, which describes the whole structural behavior with different approaches. Thus, it is for example possible to describe the supporting conditions of a structural model by fixed nodal supports, by implementation of springs or by modeling of a soil half-space. Another example for different structural models is the choice between linear and nonlinear material behavior. Thus, all models are more or less able to represent the structural system, but the quality of this approximation is sometimes very different. In order to make this clearer, find an example given in the next section.

5 APPLICATION ON A STRUCTURAL MODEL

To show that the model choice is influencing the assessment of the structural robustness, there is an example given in this section. The model describes a system of several steel columns under pressure load such that the structural system leads to buckling failures, which is a sub-area of stability failures.

The worst structural failures in steel constructions are caused by stability problems. Since failures according to stability problems are usually very abrupt and without any prior notice, the chance to prevent the collapse or evacuate people before the collapse takes place is very low. To

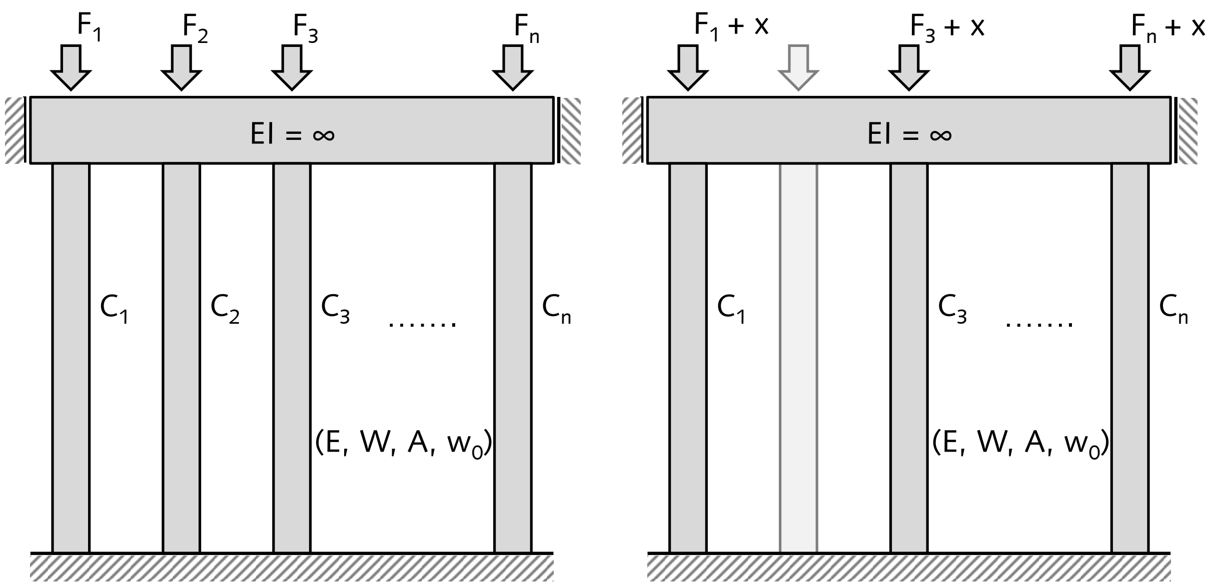

Figure 4: Structural system before and after damage occurs

avoid this type of failures, a variety of computational models still exists. These models belong to the review of load bearing capacity and the need for compliance is governed by the codes. However, the codes did not prescribe an approach for the evaluation of the structural robustness. Therefore, it is necessary to think about the usage of the risk based robustness index.

The chosen system, which is shown in figure 4, describes a structure of n columns under pressure load. These columns are arranged in a row and coupled by a beam with stiffness $EI = \infty$. The connection points of the columns are hinged, which means Euler case II. The input parameters of the structural model are stochastic, to reflect the scattering in real structures. This means that the cross-sections, material parameters, input loads and also imperfections will be described as scattering values. To show the influences of two different structural models, the evaluation was done by two different model approaches. The first model uses nonlinear kinematics to estimate the load bearing capacity, which means the deformation of the structure will be taken into account. The second model uses only linear kinematics. Thus, this means that the second model has a much poorer model quality, since it overestimates the structural behavior by a large margin.

The evaluation of the risk based structural robustness of the example shown will be done according to the event tree in figure 3. After the first exposure (EX_{BD}) occurs, the algorithm calculates the load bearing capacity of each structural member. With this, it is possible to separate into two different model responses. If there is no damage in the structure, the model response is path $\overline{D}$ - no damage occurs, and if damage occurs, the structure goes to path D. So it is possible, to estimate the probability of failure for the first step, which describes the direct failures. After damage occurs, the model rearranges the loads from the failed members to the rest of the structure. This is shown in figure 4, where x indicates the rearranged load from the failed component. By the use of the new loads, the system calculates the load bearing capacity

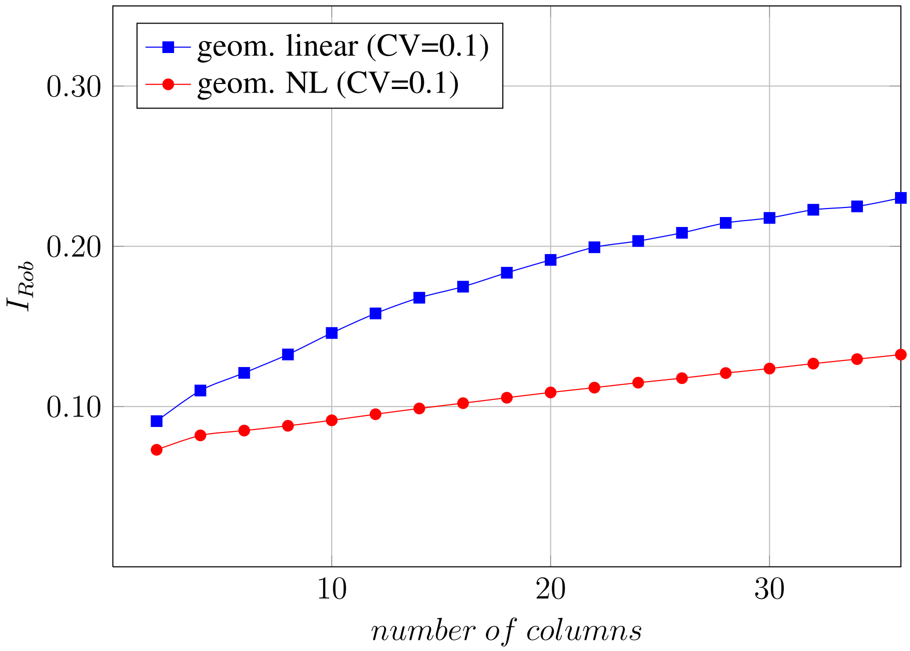

Figure 5: Risk Based Robustness Index for two different models

again. If new damage occurs the structure follows path F, and if there is no additional damage the system follows path $\overline{F}$.

According to the approach of the risk based robustness index, it is necessary to distinguish between direct and indirect risk. As mentioned before, direct risk is the probability of failure of the intact system (D), multiplied with the consequences from this direct failure. The estimation is done according to equation 3. The indirect risk is estimated according to equation 4, where the probability of failure is described by D and F. For the definition of the consequences, some assumptions were made: the consequences for the failure of one component are counted by 10, the consequences for the failure of the whole structure are counted by 1000. Thus, a failure of the whole structure will be penalized strongly.

The evaluation of the risk based robustness index is carried out for the two structural models, with geometrical linearity and nonlinearity. As shown in figure 5, the difference in the model response is really high. With an increasing number of columns in the structural models, the robustness index of both models is also increasing. But with an increasing number of columns, the difference in the model output is increasing as well. As shown, the model with the better model quality (geometrical nonlinear model), estimates a lower robustness index. This means that the model with the poor model quality overestimates the robustness of the given structure.

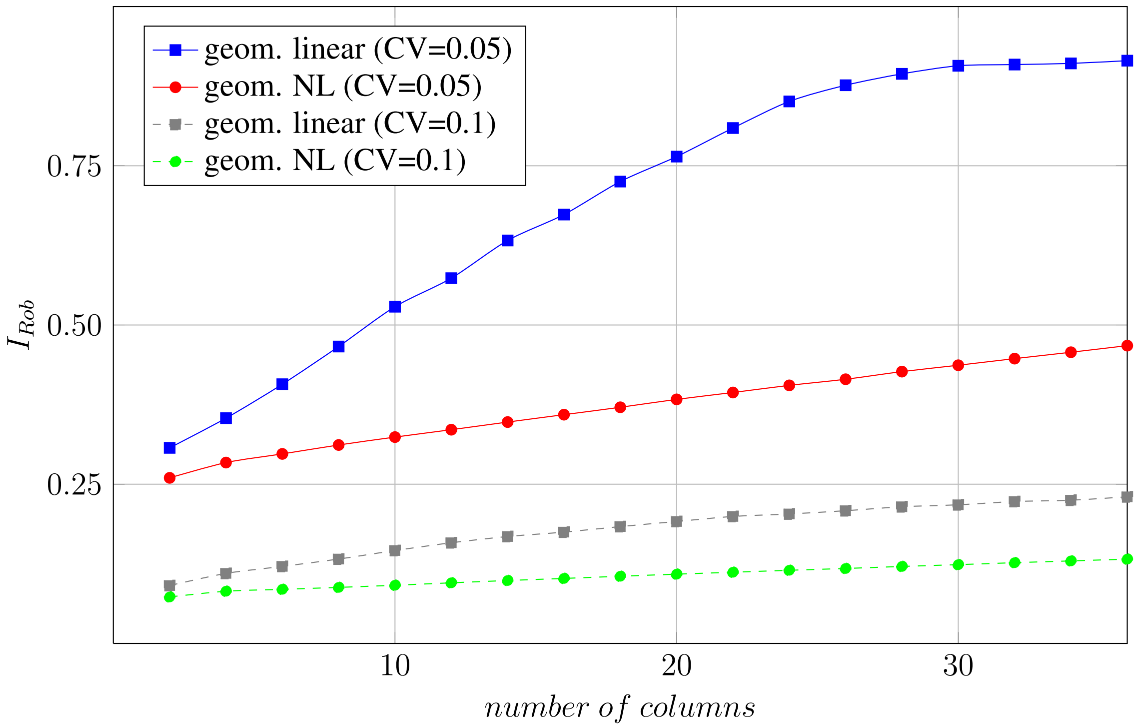

Figure 6: Robustness index for two different models and different coefficient of variation

Figure 6 shows the model outputs for both models, with a different coefficient of variation for the model input parameters. As can be seen, a smaller coefficient of variation in the input parameters leads to a higher robustness of the structural models. But the problem is that the overestimating of the poor model also increases. The linear model estimates a model robustness of up to 0.91, wherein the nonlinear model estimates a model robustness of 0.47. This means that the linear model identifies a very robust structure, wherein the nonlinear model identifies a less robust structure. So it is shown, that the influence from the structural model on the evaluation of the robustness index is very high. A correct model choice in front of the evaluation of the structural robustness is recommendable.

During the research an attempt was also made to evaluate the structural robustness for both models according to the reliability based robustness index. However, there was the problem that the usage of the reliability indices leads to a very high scattering in the model answers. Since the probabilities of failure in the used models are sometimes very small, a high scattering in the reliability indices occurs and as such, the evaluation was not meaningful. Perhaps, a model with a lesser number of stochastic input parameters will lead to usable model outputs.

6 CONCLUSIONS

In structural engineering a lot of design parameters which have to be taken into account during the design process are already in existence. One of them is the structural robustness index. However, since there is no common definition for the term *robustness* and no universal evaluation algorithm already in existence, most of the engineers did not consider this design parameter.

The topic of structural robustness has been addressed in engineering literature several times during the last years. Thereby, several evaluation approaches were developed. Two of them are the reliability based and the risk based robustness index, which have been described in this paper. For the evaluation of the risk based robustness index, an event tree that shows the different model answers according to robustness problems currently exists. The starting point of this event tree and also the basis for each robustness evaluation is the structural model. Since all the approaches for the evaluation of the structural robustness have no requirements to the quality of the used structural models, this paper shows that the chosen structural model highly influences the robustness index. In the given example of n columns under pressure load, the model with the less quality was strongly overestimating the structural robustness. This means that a poor model leads to an overestimation of the structural robustness. Thus, the question regarding the right model choice for the structural model is of utmost importance.

In the next steps, the structural model of a multi-storage frame will be used to evaluate the influences of different partial models more in detail. There, it will also be possible to show the influences of different static systems. By adding a model quality evaluation process in front of the robustness estimation, it may be possible to improve the quality of the structural robustness indices.

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