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Consideration of Partial safety factor method for snow load

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ABSTRACT: The partial safety factor method is the concept used in the current Eurocode system. Recommended partial safety factor's application should lead to results which are compatible with the safety requirements. These requirements are represented by the target values of reliability in EN-1990. Different basic variables such as actions, resistance and geometry are contributing in the reliability of structures. Variable loads and climate actions have high values of coefficient of variation. This high deviation has a strong influence in cases with high ratios of variable load to permanent actions. The reliability calculations show that in the presence of snow and low ratio of permanent load, the current partial factors are not satisfying the target reliably level. This phenomenon usually is occurring in the case of light-weight structures. In order to reach the target reliability level, more safety measures are required to be introduced for design with snow actions. A new method for applying an increasing factor for a partial factor of snow actions is proposed and investigated based on reliability analysis. Different ratios of loading with all possible load combinations in EN-1990 and different types of structure are considered to be compared with the results of the Eurocode. Application of this new strategy is providing more consistent behavior of reliability in the whole range of load ratios. Introducing the increasing factor leads to a higher reliability level.

1. INTRODUCTION

Structural components are subjected to different kinds of loading. One of the actions which has to be considered in the design process is snow load. Considerable uncertainty must be applied for modeling snow loads because of their environmental origin. Over the last 15-20 years, , snow precipitation has varies in different ways because of the phenomena of extreme climate change (Severyn et al. 2018). During 2005 and 2006 in Europe, several failures in structures occurred due to heavy snow load (Holicky and Sykora 2010). Since then, different investigations have shown the inconsistet level of safety between the designed structures and the recommended safety level in the codes (Kozak and Liel 2015). One reason for violation of safety requirements may be the insufficient safety application in structural design codes. Therefore, more safety measures must be introduced to fulfill the minimum safety requirements.

2. INTRODUCING INCREASE FACTOR FOR SNOW LOAD

An increase factor is proposed in this investigation to sustain the required safety in cases of structural design with snow load. Reliability analysis based on the combinations and a partial factor of EN-1990-1-1 (2002/2010) show that the partial factor of snow load are not enough to reach the target reliabilities. This study proposes and investigates a new method for calculation of structures subjected to snow load. This method will be applied and improved to get a consistent result with target reliabilities of Eurocode. The characteristic value of snow load for a structural component is determined based on (1).

$$S_k = s_0 \cdot c_i \tag{1}$$

where:

s_0 is the ground value of snow load based on the location elevation of the structure, or it is representing the characteristic value of the ground value of snow

c_i is the shape factor based on the form of the structure.

According to the recommended value of the characteristic value of snow load for a specific location and structural type, the design value is determined by applying a partial safety factor of snow.

$$S_d = S_k \cdot \gamma_Q \quad \text{with} \quad \gamma_Q = 1.5 \tag{2}$$

An additional safety factor has to be applied in case of snow loads. This increase factor will be applied to the partial factor of snow and increases the safety amount of the design.

Table 1: Increase factor k_s for snow load.

The ratio of snow over self-weight	increase factor k_s
$\frac{s_0}{G} \leq 0.5$	1
$0.5 \leq \frac{s_0}{G} \leq 3.0$	$0.9 + 0.2\frac{s_0}{G}$
$\frac{s_0}{G} \geq 3.0$	1.5

This increased factor k_s is defined based on the ratio of snow load to the self-weight of the structural components. According to Table 1, the minimum value of 1 and maximum of 1.5 are considered for increase factor, and a linear interpolation has to be done to determine k_s in the middle interval. The design value of snow load is determined by considering increase factor with (3).

$$S_d = S_k \cdot \gamma_Q \cdot k_s \tag{3}$$

In order to define the ratio in a normalized format, the ratio of snow load can be represented based on the total amount of load. Therefore instead of an open interval to the infinity, the values can be assigned to the so-called ratio S, which is between 0 and 1 as in (4) and Table 2.

$$S = \frac{s_0}{G + s_0} \quad \text{and} \quad \frac{s_0}{G} = \frac{S}{1 - S} \tag{4}$$

Table 2: Increase factor k_s for snow load.

The ratio of snow over self-weight and snow	increase factor k_s
$S \leq 0.333$	1
$0.333 \leq S \leq 0.75$	$0.9 + 0.2 \cdot \frac{S}{1 - S}$
$S \geq 0.75$	1.5

Based on Table 2, the increase factor k_s corresponds to snow load can be represented as in Figure 1.

These three intervals are separated based on the load's ratios. These ratios can be considered to represent the structural weight to the applied snow load. Small ranges of this ratio mean that the structure is heavy. For heavy structures, the amount of snow load in comparison with the dead load of the structure is small. Therefore, the increase factor is considered to be 1. In other words, there is no increase in the amount of snow load because it is not decisive in the design process.

In the case of the middle interval, a linear interpolation is implemented. The factor increases with the ratio. The lighter the structure is, the higher the snow load effect will be. The last interval represents the light-weight structures. In this case, the maximum value of increase factor has been considered because the snow load has a more critical role in the design.

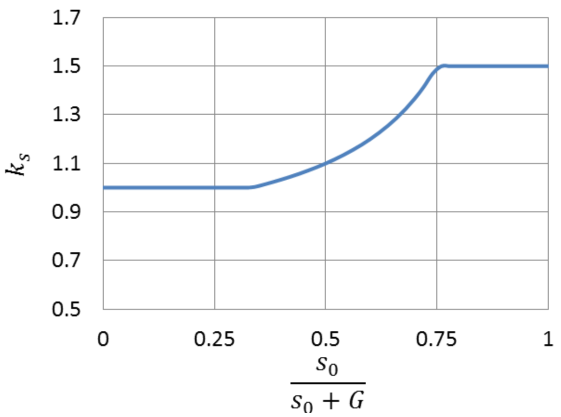

Figure 1: Increase factor k_s of snow load with $S=s_0/(s_0+G)$

3. RELIABILITY OF LOAD COMBINATIONS WITH INCREASE FACTOR FOR SNOW LOAD

In order to compare the results of this method and evaluate its differences from the EN-1990 combinations, reliability analysis with FORM (First Order Reliability Method) has been conducted. Load combinations for structural design in EN-1990, 6.10, 6.10a, 6.10b, and the combination with snow increase factor (Eqs. (5), (6), (7) and (8)) are implemented with corresponding values for partial factors and combination factors in the code. In case of load combinations 6.10a, 6.10b, the less favorable of them has to be selected. It means that these two are representing a single combination.

$$E_d = \sum_{j\geq 1}\gamma_{G,j}G_{k,j} + \gamma_{Q,1}Q_{k,1} + \sum_{i>1}\gamma_{Q,i}\psi_{0,i}Q_{k,i} \quad (5)$$

$$E_d = \sum_{j\geq 1}\gamma_{G,j}G_{k,j} + \gamma_{Q,1}\psi_{0,i}Q_{k,1} + \sum_{i>1}\gamma_{Q,i}\psi_{0,i}Q_{k,i} \quad (6)$$

$$E_d = \sum_{j\geq 1}\xi_j\gamma_{G,j}G_{k,j} + \gamma_{Q,1}Q_{k,1} + \sum_{i>1}\gamma_{Q,i}\psi_{0,i}Q_{k,i} \quad (7)$$

$$E_d = \sum_{j\geq 1}\gamma_{G,j}G_{k,j} + k_s\gamma_{Q,1}Q_{k,1} + \sum_{i>1}\gamma_{Q,i}\psi_{0,i}Q_{k,i} \quad (8)$$

$G_{k,j}$ is permanent action, $Q_{k,1}$ is leading variable action and $Q_{k,i}$ is accompanying variable load. $\gamma_{G,j}$ (1.35) is permanent load partial factor, $\gamma_{Q,1}$ (1.5) is a partial factor for leading variable load, ζ is the reduction factor for permanent loads and $\psi_{0,i}$ is the combination factor for variable loads.

The ratios between these load types are defined in (9) and (10). These values will be applied in reliability analysis to distribute the total assumed load in different types of loading to observe their influence on the reliability index. The χ value represents the structural normalized weight. If G is the self-weight of structure the high values of χ correspond to the light-weight structure and small values will be for the heavy-weight structures.

$$\chi = \frac{Q_k}{Q_k + G_k} = \frac{Q_{1k} + Q_{2k}}{Q_{1k} + Q_{2k} + G_k} \quad (9)$$

$$k = \frac{Q_{2k}}{Q_{1k}} \quad (10)$$

Table 3: Stochastic parameters (Gulvanessian 2003) (Holicky and Sykora 2011).

Basic variables	Dist.	Mean	Cov. x
Permanent	Normal	G_k	0.05
Snow (50 years)	Gumbel	$1.1Q_k$	0.30
Snow (1 years)	Gumbel	$0.35Q_k$	0.7
Imposed (50 years)	Gumbel	$0.6Q_k$	0.35
Imposed (5 years)	Gumbel	$0.2Q_k$	1.1
Structural steel	Lognormal	$R_k+2\sigma$	0.08
Steel uncertainty	Lognormal	1.10	0.07
Actions uncertainty	Lognormal	1.00	0.05

The reliability analysis is performed for a steel cross section based on the limit state in (11) with stochastic parameters from Table 3. The stochastic parameters in Table 3 are conventional values proposed in (Gulvanessian 2003) and (Holicky and Sykora 2011) for code calibration. The rule of Turkstra is applied for considering the combination of time-dependent loads (Turkstra and Madsen 1980). It means that the combination of 50 years maximum of leading action and point in time distribution (approximated by 1 year maximum for snow and 5 years maximum for imposed load) as of accompanying action (Gulvanessian 2003).

$$g = \theta_R R - \theta_E \left(G + Q_1 + Q_2\right) \qquad (11)$$

The result of reliability index for the case with only one variable load snow is shown in Figure 2. The other case with snow as the leading variable and imposed as accompanying with ratio k=0.5 is also shown in Figure 3.

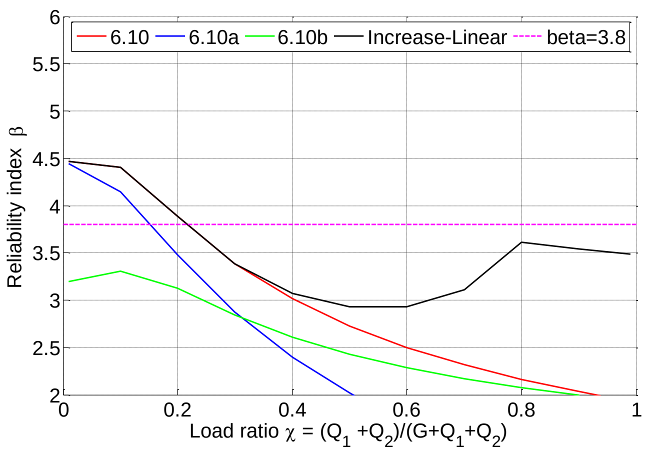

Figure 2: Reliability index for one variable load, snow load

As observed, the application of increased factor based, on the linear equation in Table 1 or Table 2 for variable loads, produces more consistent result than EN-1990. The difference between the maximum and minimum values of reliability index with an increase factor is lower than the difference of max. and min. in fundamental combinations of EN-1990. Hence, the final results demonstrate higher safety through an increase factor application for snow load with a single combination. The final result is more economical in comparsion with reccomendation in EN-1990. The reliabilities with higher ratios of χ (light-weight structures) reach values close to the target reliability.

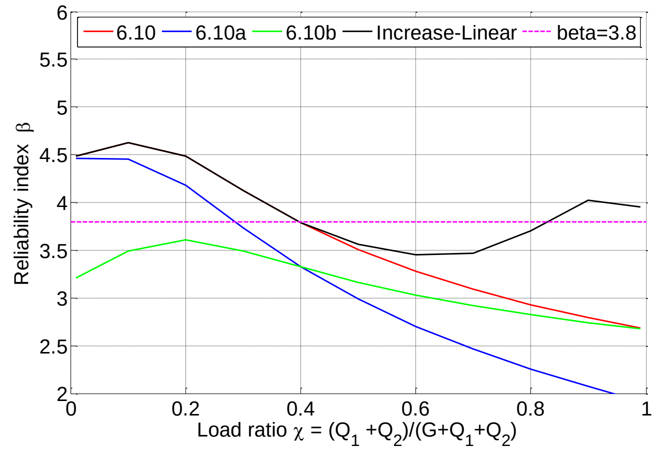

Figure 3: Reliability index for two variable loads, snow load leading and imposed accompanying

4. IMPROVEMENT OF LINEAR METHOD

An improvement in the linear method could offer better results in the middle range ratio of χ (e.g. in Figure 2, the range between 0.3 and 0.8). In this range the reliability index of the linear method is reduced, and it is below the target reliability level.

In order to overcome this problem, an improvement for the calculation of increase factor in this middle range should be applied. Based on the linear recommendation in the middle range, the increase factor has to be calculated based on a linear interpolation between 1 and 1.5. To reduce the effect of this concave area and produce a result more compatible to target reliability, the increase factor of snow has to be raised more at the beginning of the middle interval. It means that the inclination of the increase factor in smaller values of the middle range has to be higher than at the end of the middle range. Therefore, instead of a linear function for enhancing the increase factor in the middle interval, parabola functions (12) can be applied (Figure 4).

$$k_s = -0.08 \cdot \left(\frac{s_0}{G} \right)^2 + 0.48 \cdot \frac{s_0}{G} + 0.78 \qquad (12)$$

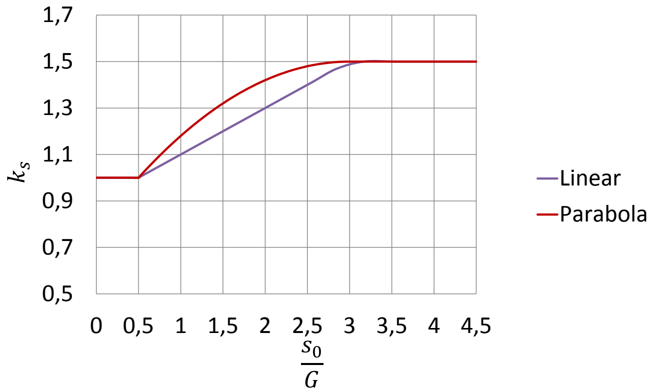

Figure 4: Linear and parabola models for calculation of k_s in middle range

The reliability analysis for comparison of these parabola methods is shown in Figure 5 and Figure 6. The resulting reliability indexes are compared with the 6.10, 6.10a and 6.10b of EN-1990. The influence of parabola application can be observed in the middle range by reaching the higher values of reliability.

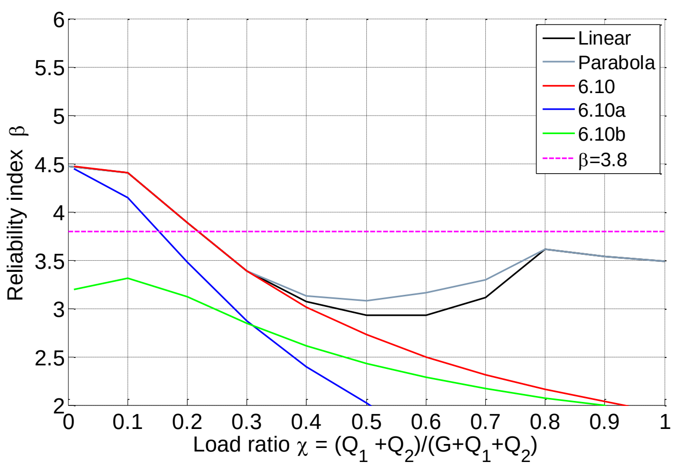

Figure 5: Reliability for linear and Parabola methods with EN-1990 combinations for k=0

In order to compare these methods with EN-1990 combinations, the deviations of the results are presented for both diagrams. The deviations are presented in Figure 7. The deviation is calculated from load combination 6.10 because in all cases it gives higher value of reliability than 6.10a&b.

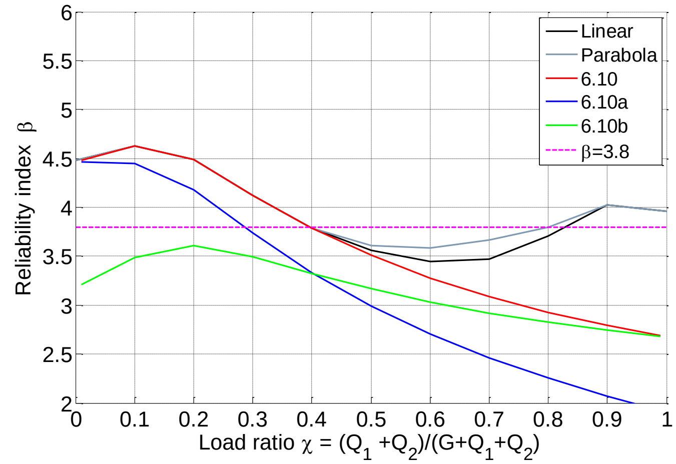

Figure 6: Reliability for linear and Parabola methods with EN-1990 combinations for k=0.5

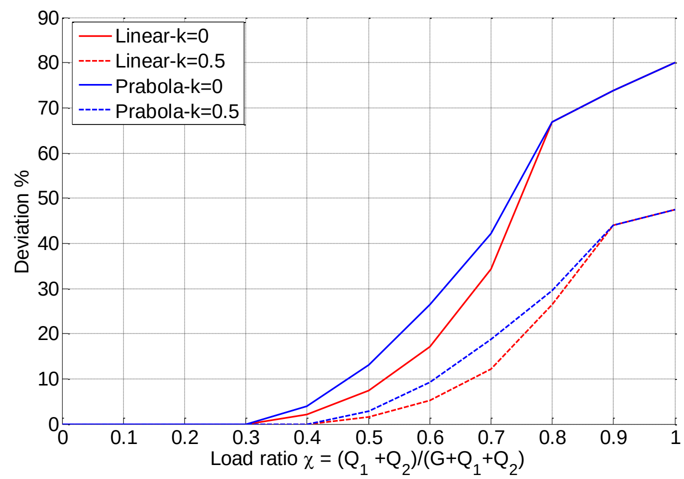

Figure 7: Deviation of increase factor methods from combination 6.10-EN-1990

The most critical range of load ratio χ in presence of snow load is in its higher values or light-weight structures. As seen, the deviation is considerable in cases with a higher ratio of variable loads. The increase factor method provide maximum 80% and 48% for k=0 and k=0.5 respectively, more safety amount in comparison with the safety provided by recommendation of EN-1990. The comparisons between the values correspond to the parabola and linear method also show that the parabola will increase the reliability at its maximum amount approximately by10 %.

5. CONCLUSION

The goal of calibration analysis is to achieve the constant reliability index with repect to the target value of reliability and providing the optimum required safety in the design process. Through reliability analysis for load combinations in the EN-1990 for the snow load, it has been observed that the resulting values of reliability are not consistent with regards to the target reliability in the whole interval of load ratios. Moreover, the results show that the safety level provided by EN-1990 combinations is lower than the required level in the code. The current amounts of safety according to EN-1990 are significantly lower than the target reliability in high ranges of load ratio χ which represent the light-weight structures.

Application of the recommended method, an increase factor for snow load, produces safer result. The reliability levels of EN-1990 load combinations show unacceptable results in case of high amount of variable loads. In these cases, the maximum deviation of increase factor method from load combination 6.10 is nearly 80%. The reliability behavior leads to the conclusion that the structures with low permanent actions or self-weight (e.g. industrial sheds, roofs, etc.) are more sensitive to the lack of safety in the case of snow loads. Therefore, the maximum value of increase factor belongs to this interval of load ratio where light-weight structures are located. The improvement of linear interpolation with a parabola function is enhancing the reliability level and produces more consistent result with respect to target reliability. The outcome of this consistency is a safe and economical design.

Eventually, it can be concluded that the application of different increase factor according to the load ratios in three intervals instead of a single value of increase factor for whole range of load rations is more reasonable. The advantage of this method is that the result is neither conservative in small ranges of χ nor unsafe in high ranges.

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