IMPLEMENTING SNOW LOAD MONITORING TO CONTROL RELIABILITY OF A STADIUM ROOF

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Abstract. *This contribution shows how monitoring can be used to control reliability of a structure not complying with the requirements of Eurocodes. A general methodology to obtain cost-optimal decisions using limit state design, probabilistic reliability analysis and cost estimates is utilised in a full-scale case study dealing with the roof of a stadium located in Northern Italy. The results demonstrate the potential of monitoring systems and probabilistic reliability analysis to support decisions regarding safety measures such as snow removal, or temporary closure of the stadium.*

Keywords

Cost optimisation, decision making criteria, Eurocodes, monitoring, reliability analysis, snow load, stadium roof, standard.

1. Introduction

The quantification of value of information of Structural Health Monitoring (SHM) is a major issue for new and existing structures. The EU COST TU1402 project deals with the quantification of the value of information of SHM by a novel utilization of applied decision analysis. Knowing the value of SHM, one can improve the decision basis for the design, operation and life-cycle integrity management of structures, while facilitating more cost efficient, reliable and safe strategies for maintaining and developing the built environment to the benefit of society. Therefore, it is essential to provide guidelines for practicing engineers and to illustrate their applications by comprehensible case studies.

The implementation of a draft guideline currently under development within COST Action TU1402 [1] and of the related risk-based approach is illustrated in the full-scale case study of the roof of a stadium. As the roof fails to comply with the requirements of the Eurocodes, a permanent monitoring system has been designed utilising the experience of the industry and academia. The contribution extends the previous studies [2] and [3].

2. Reliability analysis

The stadium erected at the beginning of the 1990s is located in Northern Italy, at an altitude of 190 m [2]. The roof consists of cantilever steel beams IPE450 (Fig. 1) with spacing of 5 m. The capacity of the open-roof stadium is 4000 persons. In winter it is occasionally used to host sport events. As the structure is located in the Alpine region and may be subjected to snow loads, an assessment of its actual structural reliability has become an important issue following the recent roof collapses and reliability analyses of structures subjected to snow loads [4], [5], [6] and [7]. The case study is focused on the Ultimate Limit State verification only.

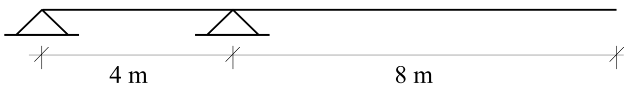

Fig. 1: Scheme of the roof beam.

The analysis of past and present standards reveals that the design snow loads have increased significantly over recent decades. The former Italian standard D.M. 12.02 [8] assumed the characteristic snow load for zone I – applicable to the stadium – of 0.9 kN/m^2; the current code consistent with EN 1991-1-3 [9] gives $s_{g,k}$ = 1.2 kN/m^2. These values indicate that the currently posited snow loads exceed those considered in the design. Consequently, many existing structures, whose reliability is dominated by snow loads, do not comply with the requirements of the Eurocodes. The resistance of the roof is about 90% of the design value required by the Eurocodes. This could be authorised by accepting a lower target reliability for an existing structure [10] and [11]. However, the responsible authority disapproves with this possibility and requests that the safety-critical structure (CC3 according to EN 1990 [12]) comply with the requirements of Eurocodes.

In order to keep the reliability level of the stadium acceptable, the reliability of the roof is analysed by probabilistic methods. This is to support the decision regarding the use of the stadium and the implementation of a permanent online monitoring system. A three-day weather forecast is considered to provide the decision-maker with flexibility to implement the safety measures.

The structural performance for the key roof component – the cantilever beam in Fig. 1 – is first assessed by a reliability analysis. The limit state function for the section of the beam subjected to the maximum bending moment due to permanent actions and annual maxima of snow load reads:

$$Z(\mathbf{X}) = R - \theta_E\,(G + \mu\,S + \Delta S). \qquad (1)$$

The probabilistic models of the basic variables given in Tab. 1 are selected following the JCSS recommendations [13]; see [2] for details. Since the roof is flat and without any obstacles, the snow load dominates and the wind effects are neglected. When considering Gumbel distributed annual maxima of the ground snow load for the location – mean 0.55 kN/m^2 and CoV 60%, and ΔS = 0 kN/m^2, the obtained annual reliability index of 4.0 is significantly below the annual target level of 5.2 given in EN 1990 [12] for CC3, as expected for structures with a dominating snow load [6] and [7]. This is why the application of roof snow load monitoring – previously selected out of three monitoring alternatives [2] and [3] – is investigated to indicate how roof reliability can be controlled. Note that the value of 0.8 adopted in Tab. 1 for the shape factor might be slightly conservative for some (windswept) roof areas, but generally seems to be confirmed by the wind tunnel tests for flat roofs of open stadia [14].

3. Monitoring strategy and intervention actions

Following recommendations of a technology provider, roof snow loads should be measured at each 500 m^2 and about 6 sensors should be installed on the roof. Acquisition cost is 28000 € for two sensors and annual operational cost (replacement every 20 years) is ~1600 €/year. The accurate estimates of the roof snow load significantly reduce uncertainty in the shape factor. The most unfavourable measurement is taken into account once it is proven that it is an outlying observation (considering measurements of the other five sensors).

Tab.1: Models of basic variables – adapted from [2].

Variable	Distr.	Mean / char. value	CoV in %
Plastic flexural resistance including model uncertainty, R	LN	1.28	8.6
Load effect uncertainty, θ_E	LN	1	5
Moment due to self-weight and due to roofing, G	N	1	4
Shape factor, μ: no monitoring / monitoring on roof	N	1 (μ = 0.8/ 1)	15/ 5
Moment due to measured snow load S	N	measured	Standard deviation σ = 0.1 kN/m^2 (measurement uncertainty)
Snow load predicted for next three days, ΔS	LN	Expected increment of ground snow load for major annual snowfall in upcoming three days - 0.3 kN/m^2.	50

When a specified threshold is exceeded, various interventions can be considered:

- cleaning of the roof by specialists, ≈ 30 000 € = 30 k€,
- temporary closure for one or two weeks – highly season-dependent, slightly exceeds the cleaning cost when the stadium is fully utilised,
- do nothing (accept the risk).

Though this decision could also be optimised, only the cleaning option is considered hereafter for reasons of brevity.

4. Cost modelling

Structural costs and costs of monitoring can be assessed based on available data from the industry. Failure costs were investigated in [15], including demolition cost, economic losses due to non-availability of the stadium and societal consequences – costs of injuries and fatalities for two scenarios – failure when the stadium is empty or by 50% full (expected number of spectators in a winter season). Considering large uncertainties in the consequence analysis, a wide range of failure consequences <570, 7500> k€ was estimated. The other consequences – environmental, loss of reputation, introducing undesirable 'non-optimal' changes of design practice etc. [16] – are ignored here.

5. Risk acceptance criterion for temporary situation

The target reliability level needs to be specified for the situation when a limiting value of the roof snow load s_{lim} is exceeded and a safety measure must be implemented. Target levels for such temporary situations – typically about two weeks for the location under consideration – are not provided in standards. Recently, Tanner and Hingorani [17] proposed a procedure to derive target levels for short-term situations; however a widely accepted and standardised approach is unavailable.

The previous study [3] showed that the annual target level of 5.2 given in EN 1990 [12] for CC3 structures or the application of the partial factors for structural design lead to overly conservative thresholds. Alternatively, a cost-benefit analysis can be conducted to decide about the use of the stadium on the basis of the balance between safety measure cost and the expected failure consequences. This strategy is supported by the reliability management in EN 1990 [12]: "The choice of the levels of reliability for a particular structure should take account of the relevant factors, including the possible cause and /or mode of attaining a limit state, the possible consequences of failure in terms of risk to life, injury, potential economic losses, public aversion to failure and the expense and procedures necessary to reduce the risk of failure."

Snow on the roof is removed whenever the risk – failure consequences C_{f} multiplied by failure probability $p_{\mathrm{f}}(S_{|S>s\mathrm{lim}})$ given the roof snow load exceeds the threshold – becomes larger than the cost of safety measure C_{safe}:

$$C_{\mathrm{safe}} + C_{\mathrm{f}}\, p_{\mathrm{f}}(S = s_{\mathrm{lim}} + \Delta S/2) \leq C_{\mathrm{f}}\, p_{\mathrm{f}}(S_{|S>s\mathrm{lim}}), \qquad (2)$$

where s_{lim} denotes the threshold, whose optimum value is obtained when both sides of Eq. (2) are equal. The second term of the left-hand side of Eq. (2) accounts for a small probability that failure occurs in the period from the time of the warning to the snow removal when approximately half of ΔS accumulates on the roof. The probabilistic model of $(S = s_{\mathrm{lim}})$ is a normal distribution with the mean equal to the threshold and standard deviation of the measurement uncertainty (Tab. 1). The probabilistic model of $(S > s_{\mathrm{lim}})$ can be obtained as a Gumbel distribution truncated at the threshold considering the uncertainty in s_{lim} (in kN/m^2):

- For no uncertainty in s_{lim}:

$$\mathrm{F}_{S>s\mathrm{lim}}(s|s_{\mathrm{lim}}) = \mathrm{F}_{\mathrm{Gum}}(s, \mu \approx 0.8 \times 0.55; V \approx 0.6) / \\ / [1 - \mathrm{F}_{\mathrm{Gum}}(s_{\mathrm{lim}}, \mu; V)]; \text{ for } s \geq s_{\mathrm{lim}};\ 0 \text{ otherwise}, \qquad (3)$$

- With uncertainty in s_{lim}:

$$\mathrm{F}_{S>s\mathrm{lim}}(s|s_{\mathrm{lim}}) = \\ = \int_{-\infty}^{\infty} \mathrm{F}_{S>s\mathrm{lim}}(s|x)\mathrm{f}_{\mathrm{N}}(x, s_{\mathrm{lim}}, \sigma = 0.1)\mathrm{d}x, \qquad (4)$$

where F denotes the cumulative distribution function, f is the probability density function (PDF), and N is a normal distribution.

Using Eq. (4), Fig. 2 displays the PDFs of the roof snow loads when cleaning is and is NOT applied - $(s_{\mathrm{lim}} + \Delta S/2)$ and $(S > s_{\mathrm{lim}})$, respectively. Two thresholds corresponding to characteristic and design snow load are considered. In addition, the PDF of normalised resistance $(R - K_E G)$ is also plotted in the figure. Apparently, the scatter of $(s_{\mathrm{lim}} + \Delta S/2)$ is much smaller in comparison to $(S > s_{\mathrm{lim}})$. While the former is dominantly affected by measurement uncertainty with limited contribution of the uncertainty in weather forecast, $\Delta S/2$, the latter essentially represents the tail of extreme roof snow loads for higher thresholds. Note that the curves of $(S > s_{\mathrm{lim}})$ are not sharply truncated due to measurement uncertainty in s_{lim} in Eq. (4).

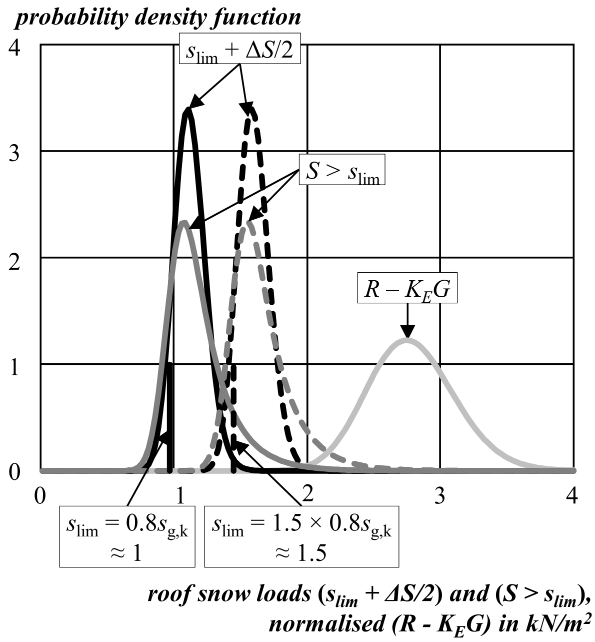

Fig. 2: PDFs of the roof snow loads when cleaning is and is NOT applied (black and dark grey curves, respectively) for the thresholds corresponding to characteristic and design snow load (solid and dashed curves, respectively) and PDF of normalised resistance (R - $K_E G$, light grey).

Using Eq. (1), the probabilistic models in Tab. 1 and the roof snow loads according to Eqs. (3) and (4), Fig. 3 shows the variation of reliability index β with the threshold s_{lim} for the two situations – when cleaning is and is NOT applied (black and grey curves, respectively). The range of s_{lim} is from 0.45 to 2 kN/m^2; the lower bound corresponding to the mean annual roof snow load; 0.8 × 0.55 kN/m^2. The low thresholds, say up to 1 kN/m^2, seem to be conservative with $\beta(s_{\mathrm{lim}} + \Delta S/2) > 5.5$. By contrast, the safety measure becomes inefficient when the threshold significantly exceeds the design value – for s_{lim} around 2 kN/m^2 the difference between $\beta(s_{\mathrm{lim}} + \Delta S/2)$ and $\beta(S > s_{\mathrm{lim}})$ reduces as failure is likely before the threshold is reached.

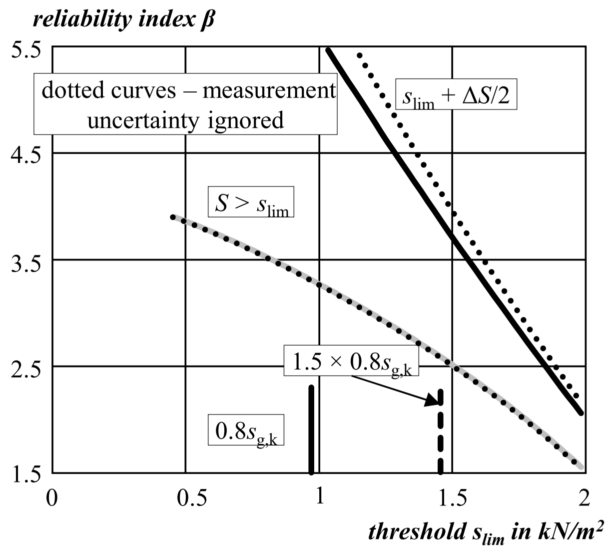

Fig. 3: Variation of reliability index β with the threshold s_{lim} when cleaning is and is NOT applied (black and grey curves, respectively).

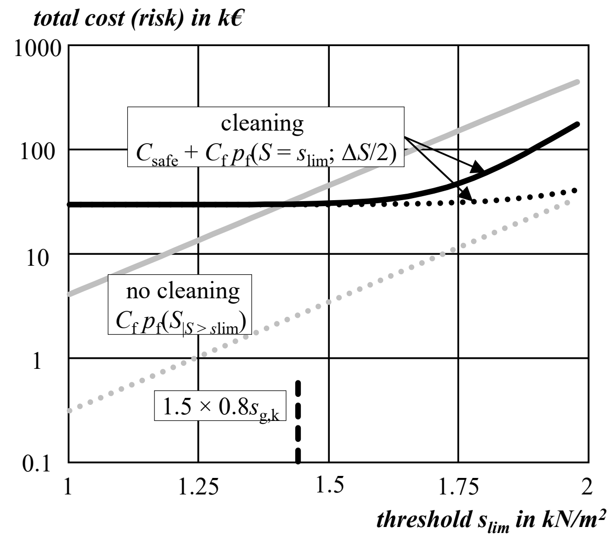

Fig. 4: Variation of the total cost (risk) in k€ with the threshold s_{lim} (dotted and solid curves – the lower and upper bound on C_f, respectively).

While $\beta(s_{lim} + \Delta S/2)$ can be easily evaluated by the standard reliability methods in available software products, the distribution of $(S > s_{lim})$ according to Eq. (4) needs to be either numerically evaluated or a double-loop application of a reliability method such as FORM/ SORM is needed [18]. This is why the effect of measurements uncertainty is investigated to indicate whether or not the application of Eq. (4) is necessary. The dotted curve in Fig. 3 suggests that, in the case under consideration, measurement uncertainty can be ignored and $\beta(S > s_{lim})$ can be evaluated using Eq. (3). Figure 3 also shows that the effect of measurement uncertainty on $\beta(s_{lim} + \Delta S/2)$ is minor. In both cases the uncertainty in s_{lim} is lower in comparison to the variability of:

- the ground snow load and shape factor $(S > s_{lim})$,
- the predicted roof snow load ΔS,
- the time-invariant variables.

However, these observations cannot be readily generalised.

Using Eq. (2), the assumed costs C_{safe} and C_f, and the reliability indices in Fig. 3, Fig. 4 displays the variation of the total cost (risk) in k€ with the threshold s_{lim}. Considering the upper bound on C_f (solid curves) and the predicted increase in the ground snow load, it follows that snow should be removed from the roof in three days since a measured roof snow load reaches 1.4 kN/m^2 (hence slightly less than the design roof snow load). When a lower threshold is selected, the cleaning cost exceeds the risk related to possible structural failure while thresholds above 1.4 kN/m^2 imply expected failure consequences higher than the cleaning cost. It is interesting to note that an optimum threshold around 2 kN/m^2 would be obtained when a lower bound on failure consequences is considered.

6. Risk acceptance criterion for temporary situation

The following observations might be useful when designing monitoring systems for snow-dominated structures:

1. The optimum threshold of 1.4 kN/m^2 corresponds to the acceptable reliability index of 4.05; see Fig. 3 and the curve of $\beta(s_{lim} + \Delta S/2)$. It is emphasised that this value is related to a temporary situation and cannot be directly compared with the annual or lifetime target levels provided in standards.

2. Estimating the threshold by the partial factor method recommended for structural design leads to very conservative thresholds (~1 kN/m^2) in the case of this stadium [3].

3. In general the specification of the acceptable reliability level requires applying the probabilistic risk analysis. When a broader consensus on acceptable criteria for selected situations such as monitoring of roofs under snow is reached, it will be possible to obtain the threshold by the Design Value Method or by the Adjusted Partial Factor Method introduced in the recent documents [19] and [20].

4. The optimum threshold is associated with a very long expected return period (190 y.), implying that safety measures will be unlikely needed. Note that the return period is estimated on the basis of available ground snow load records from the location (1973-2015) from which the distribution of a single snowfall and an average number of snowfalls per winter season (three per year – typical for maritime and continental climate) was inferred [2].

5. Another alternative for monitoring is online displacement or deformation measurements. These might:
   - Improve monitoring results in a case with drifted, spatially variable snow distributions. However, significant drifts are uncommon for large flat roofs [21].
   - Help to control hidden deficiencies of the structure, though this is unlikely for the structure more than 20 years old. Uncertainties related to displacement or deformation measurements would need to be carefully evaluated, taking into account the noise effects due to the variation of ambient air temperatures below and above the roof.

7. Concluding remarks

A draft guideline regarding structural health monitoring (SHM) for practicing engineers is being developed within COST Action TU1402. Its various steps are applied in the presented case study of a stadium roof under snow load. The roof does not comply with the requirements in EN 1990 and the snow load dominates structural reliability. A continuous monitoring of snow loads helps to assess the risk of using the structure. When a specified limiting value of the monitored parameter is exceeded, either the snow on the roof can be removed or the stadium can be temporarily closed. SHM systems allow for a real time performance evaluation and support decisions regarding safety measures.

The case study shows that the design of SHM is a complex issue that may include component / system structural reliability analysis, identification of possible monitoring strategies, specification of threshold values for observed variables, and selection of a monitoring strategy based on total cost optimisation, considering also a ‘no monitoring’ alternative. The case study provides findings specific to snow-dominated structures:

- The fact that the safety-critical structure fails to comply with the requirements of standards might be disturbing. However, the detailed probabilistic analysis helps to better understand and control the associated risks – the return period for an excessive snow load can be as long as 190 years, hence no safety measures need to be hastily taken given adequate maintenance is guaranteed.
- An important aspect of SHM design is the feasibility analysis of the possible safety measures; in the case study a three-day weather forecast is thus taken into account to provide time to remove snow from the roof.
- Cost-benefit analysis helps derive more realistic case-specific target reliability for exceeding a limiting snow load. Particularly in regard to snow loads, the Eurocode target levels seem to be too high, as is also demonstrated by the fact that the partial factor design of snow-dominated structures leads to lower reliabilities than those required by Eurocodes.
- The specification of thresholds of observed variables is a demanding task and depends on an adopted target reliability level. In the presented case, overly conservative estimates are obtained by using the partial factors recommended for structural design.
- The optimum alternative of SHM is affected by its acquisition and operational costs, and the expected cost of safety measures over a specified remaining working life.

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