SHM System for the Roof Structure of a Trade Market Hall

Y. PETRYNA and M. LEITEL

ABSTRACT

In the present work, a rational monitoring concept has been proposed for the roof structure of a large trade market hall. It is based on a preliminary structural analysis of the carrying structure and the experience from the measurements on a test structure. The number of sensors and their type is selected according to the goals of monitoring, efficiency and redundancy reasons.

INTRODUCTION

A collapse of the winter sport hall in Bad Reichenhall in 2006 gave a new impulse to the assessment of structural safety of public buildings in Germany. New attention has been paid to robust constructional designs as well as structural health monitoring of the carrying structures. Numerous professional discussions have finally led to a new guideline of the German Association of Engineers VDI 6200 “Structural safety of buildings - Regular inspections” [1]. It defines a general procedure to assess structural safety for the persons in charge including the risk classification of buildings on the basis of damage and robustness classes. In well-founded cases, the guideline recommends the application of structural health monitoring systems. Due to a wide variety of structural systems and a uniqueness of each individual building, there are no detailed recommendations regarding such SHM systems.

The present paper deals with the steel roof structure of a large trade market hall, which shall be instrumented in order to monitor the safety with respect to snow loading [2].

Y. Petryna, M. Leitel, *Technische Universität Berlin, Sekr. TIB1-B5, Gustav-Meyer-Allee 25, 13355 Berlin, Germany*

PRELIMINARY INVESTIGATIONS ON A TEST STRUCTURE

At first, intensive preliminary investigations have been performed on a selected test structure in our laboratory in order to check heterogeneous measurement equipment and the monitoring approach. This structure was a pavilion for heat flow experiments. An inclined loading rig has been specially mounted for horizontal loading (Figure 1). The response of the test structure to vertical and horizontal loading should be assessed by means of numerical simulations and measured by diverse sensors.

Figure 1. Test structure (left) and horizontal loading by a sandbag (right).

Test structure

The pavilion under consideration is a 6,4 x 5,4 x 3,7 m welded steel frame structure. The four columns have a rectangular hollow cross-section of 160 x 160 mm and a wall thickness of 10 mm. The four girders have a similar cross-section of 200 x 120 mm and also a wall thickness of 10 mm. Furthermore, three additional hollow-section profiles are arranged at the bottom of the four columns as fender.

The pavilion is insulated from the environment by glass panels which are set in between the carrying structure and shall be statically decoupled from it.

Two-thirds of the thermally insulated, bifid roof of the pavilion is removable. The smaller part is fixed with the steel frame. The removable part of the roof is framed by angle profiles with a cross-section of 160 x 160 mm and a thickness of 16 mm. The inner parts of the whole roof consist of further steel profiles, where the thermal insulation lies in between. Steel gratings and a hand rail make the whole roof walkable.

The carrying structure is made of construction steel S235 with a yield stress of $\sigma_y = 240$ N/mm², an elasticity modulus of $E = 210000$ N/mm² and a material density of $\rho = 7850$ kg/m³.

Finite element modelling

The finite element model of the test structure has been developed within the Abaqus Finite Element software [3]. At that, the roof construction has been modelled by a girder grid. The model has been verified by means of vertical deflections of several reference points under dead load. The glass panels have not been included into the model as they should not have any bearing function.

Classical Euler-Bernoulli beam elements and a linear material model have been used for the frame structure. The accuracy of numerical simulations has been checked by the convergence of numerical results during the mesh refinement. Some components experiencing only axial forces have been modelled by truss elements, for instance, the inclined loading rig for the application of horizontal loading. Figure 2 shows the rendered model of the test structure.

Figure 2. Rendered finite element model of the test structure.

Loading program

Several loading scenarios have been defined consisting of both vertical and horizontal forces, in order to be able to study the structural response under snow and wind loads. The loads have been applied by means of sandbags of 1000 kg each, placed as spatially symmetrical or asymmetrical collectives. The magnitude of the loads has been selected in such a way that deflections and strains become well measurable but the material behaviour reins elastic. Figure 3 (left) shows the location of the sandbags on the roof and the inclined rig.

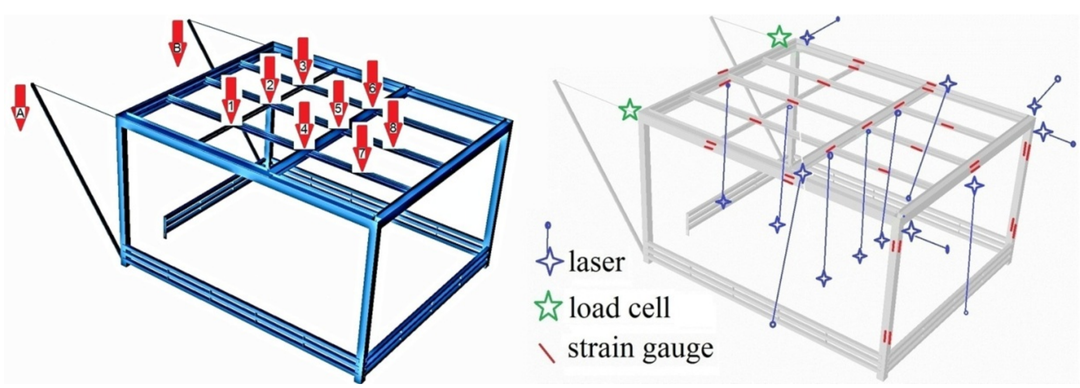

Figure 3. Points of load application (left) and sensor positions (right).

Measurement program

The measurements on the test structure shall serve to determine the applied loads and the structural response. The weight of the sandbags has been proved in advance. The magnitude of the horizontal loads applied by the inclined loading rig has been directly measured by the load cells.

The structural response has been measured by means of local strains at several reference positions as well as by global deflections of several reference nodes of the frame. The location and direction of the measured quantities are given in Figure 3 (right). Altogether, two load cells, 29 strain gauges and twelve laser distance meters have been used.

The types of sensors are shown in Figure 4. A description and characterization of the sensors in use is given in Table 1. The major measurement equipment has been provided by our industrial partner, Prometheus GmbH & Co. KG, Löningen, Germany [4].

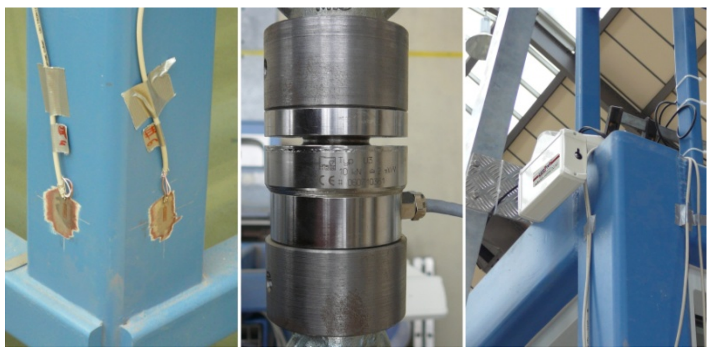

Figure 4. Strain gauges (left), load cell (middle) and laser (right).

Table 1. Description and characterization of sensors in use.

sensor	**type**	**manufacturer**	**properties**
strain gauge	PFL-10-11	Tokyo Sokki Kenkyujo Co., Ltd.	– gauge length = 10 mm – resistance: 120±0,3Ω – k = 2,12...2,13 (±1%)
load cell	U3	Hottinger Baldwin Messtechnik GmbH	– max. load = 10 kN (≈1 t) – resolution: 2 mV/V±0,2%
laser distance meter	deflection control DC-32	Prometheus GmbH & Co. KG	– accuracy: ±0,2 mm

Comparison of simulation and measurement

The measured values of the strains and displacements have been compared to the results of the finite element simulation. Only summarized results are discussed here. More details will be given in the oral presentation at the workshop.

In fact, simulation results have been actually obtained for the idealized structural model with simplified boundary conditions. Although the real structure seems to be quite simple, there are still several aspects, which have not been properly taken into account in the first study. This fact results in a quantitative difference of deflection values between simulation and experiment, especially of the strain values. Sometimes, the measured response exhibited even qualitative differences to simulations, for instance for the horizontal loading.

Nevertheless, essential aspects of the response could be satisfactorily mirrored by the model, for example, symmetrical deflections under symmetric loading, a linear relation between displacements and strains, etc. The observed differences are mainly caused, in our opinion, by incomplete boundary conditions for the roof elements and by neglecting the glazing in the model. Evidently, there was a certain coupling between the frames for the glass and the bearing structure resulting in unexpected support conditions.

The lessons made from this preliminary study are as follows. It is generally possible and necessary to develop a structural model for the assessment and monitoring. This model needs however a thorough checking with respect to numerous constructional details, especially in support conditions. Even for the best possible model and sensor equipment, a calibration of the monitoring system on-site is inevitable.

SHM CONCEPT FOR THE ROOF STRUCTURE OF A TRADE MARKET HALL

The present work deals with the steel roof structure of a large trade market hall, which shall be instrumented in order to monitor the safety with respect to snow loading. The dimensions of the building are 120 x 78 x 9 m. The concept of the SHM system shall fulfil two goals. First of all, it shall be able to observe and estimate the snow loads on the roof and generate reliable warning signals in case of local or global overloading. The second goal is to observe the overall structural behavior and detect events of abnormal or nonlinear response, which can mean damage and change of the carrying capacity. The instrumentation of the carrying structure shall be planned with commercially available sensors and measurement techniques and be cost-efficient as far as possible.

Geometry and carrying structure

The roof carrying structure is built on a grid of concrete columns with individual foundations and has span widths of 14 and 21 m. The main steel trussed girders with a span of 14 m are placed on the columns and serve as supports for the steel cross girders of 21 m length, which are designed as cable-trussed girders as shown in Figure 5. The latter bear the steel roof with trapezoidal sheeting.

Some parts of the building at the periphery are designed for special purposes and possess individual bearing structures. However, these parts are marginal and do not affect the overall behaviour of the finite element model.

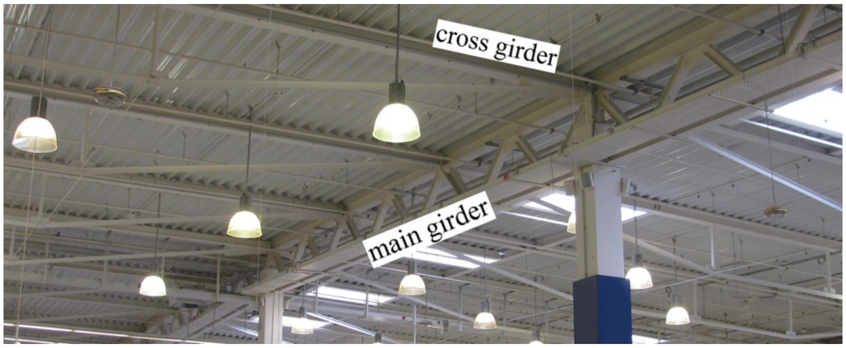

Figure 5. Bottom view of the roof structure.

Finite element modelling and analysis

The bearing structure has been modeled within the Abaqus Finite Element software [3] with use of beam and truss elements. Linear elastic behavior is assumed both for steel and concrete members. For simplicity, the trapezoidal sheets of the roof have been replaced by displacement-equivalent flat plates. These plates are then subjected to snow loading. Figure 6 shows the entire finite element model. This structure consists of several equal cells containing two main girders and four cross girders each.

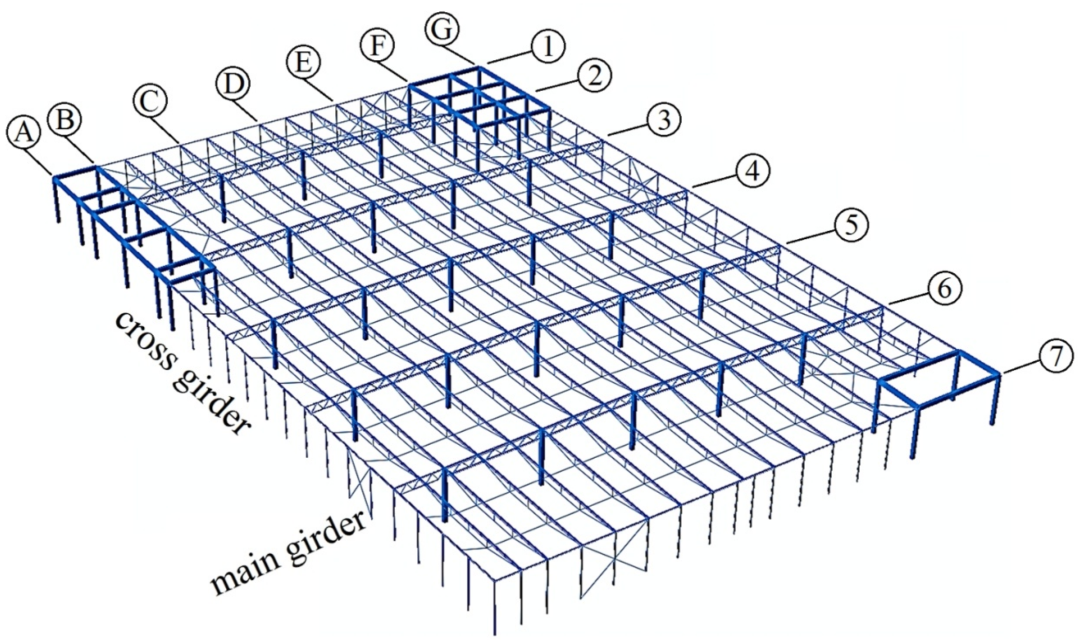

Figure 6. Rendered model of the trade market hall without roof plates.

At first, a linear structural analysis has been performed in order to study the overall behaviour under uniform snow loading as well as individual loading of only one cell due to snow banks. At that, characteristic vertical displacements and strains help to define the number and location of suitable reference points for subsequent measurements.

As can be seen from Figure 7, the deflections of the roof under uniform snow loading over the entire surface do not generally differ from the roof deflection of only one cell under an individual snow loading.

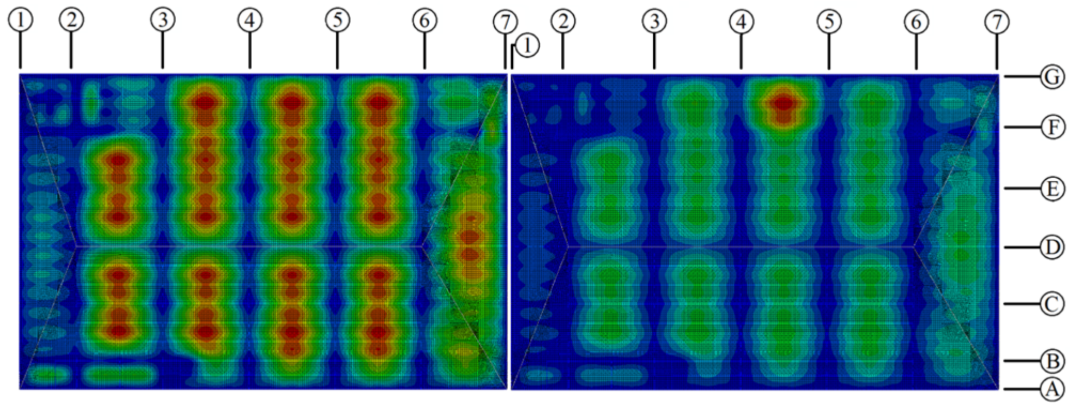

Figure 7. Vertical displacements of the roof under dead weight and uniform snow loading (left) and dead weight and individual loading of one cell (right), maximum deflection of 68 mm (red).

The main conclusion is that each cell shall be monitored individually. In order to guarantee the safety of the whole structure, monitoring every cell seems to be inevitable, since the position of the snow banks cannot be predicted in advance. From the analysis of the bearing structure follows also, that static stability problems are not relevant and no special monitoring in this context is required.

In addition, it has been proved that the roof deflection in each cell consists of three components: the plate deflection, the cross girder displacement and that of the main girder. The major portions result from the cross girder and the trapezoidal sheets. The deflection of the sheets exhibits strong variation depending on the load distribution on the cell. If the snow loading is not uniform, the position of the maximum displacement is then hard to be determined.

On the other hand, the construction of the cross girder presumes the same tensile strains in the whole mid-cable. These strains are proportional to the cross girder displacement and easier to be measured.

Proposed SHM concept

Taking into account the above results, the following monitoring concept is proposed. Each construction cell shall be individually monitored by measuring tensile strains in the mid-cable of at least one of the middle cross girders. The proportionality factor between these strains and the vertical deflection of this girder has to be calculated in advance and calibrated by test loadings.

For redundancy, two strain gauges can be installed on the reference girders. Thus, totally 23 x 2 = 46 strain gauges are required for the entire structure. In addition, several laser distance meters shall be installed in some cells to get independent data on displacements for a comparison with the measured strains. The number of distance meters affects the total costs and therefore needs to be discussed with the client. The instrumentation of a representative construction cell is shown in Figure 8.

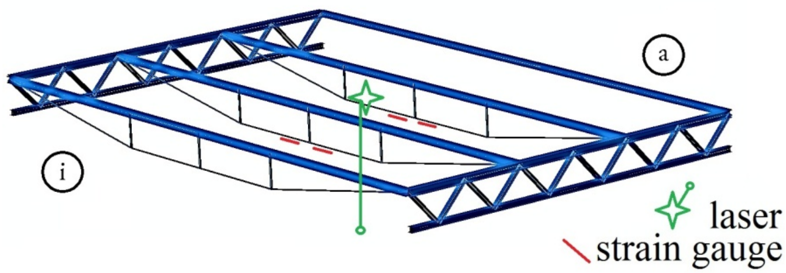

Figure 8. Concept for roof cell monitoring.

The overall behaviour of the structure can be monitored by a comparison of the strain values in all cells. For typical uniform snow loadings, all strains should be quite similar. Essential differences can indicate either local overloading of cells due to snow banks or a sensor error. Both cases require a warning and an operational action.

Furthermore, a few temperature sensors should be installed to observe the inner temperature in order to recognize contingent temperature-induced strains.

CONCLUSION AND OUTLOOK

In the present work, a rational monitoring concept has been proposed for the roof structure of a large trade market hall. It is based on a preliminary structural analysis of the carrying structure and the experience from the measurements on a test structure. The number of sensors and their type is selected according to the goals of monitoring, the efficiency and the redundancy reasons.

The present study and proposal is currently used to apply for a joint research project aiming at a continuous monitoring of this trade market hall. In the course of the project preparation, several problems still need to be solved. For instance, a rational design of a sensor grid, the energy supply and the aspects of data acquisition, storage and processing in the remote modus have to be investigated. These considerations are subject of on-going activities.

REFERENCES

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