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Monitoring and identification of structural damages

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1. Introduction

A reliable evaluation of structural integrity becomes especially important at design, manufacture and service stages in objects of increased risk. The analysis of standard structures and estimation of their functionality for a resource period usually are performing by regulations and norms, which are based on the huge theoretical and practical experience [1-3]. These regulations and norms however cannot be easily applied to items of unique structure without additional detailed and comprehensive analysis [4, 5]. This is why at present it is allocated to work of development and improvement of structure strength prediction methodologies and technologies. Such activity takes place in different areas such as civil engineering, transportation, power industry and others [6, 7].

Structural health of buildings can be supported by performing constant building maintenance by various and different means. With the help of monitoring systems the defects and damages, which occurring due to external and internal factors, changes in the building structure, ageing of utility infrastructure and technological equipment, are identified [8, 9]. The constant monitoring helps protect buildings against dangerous collapse phenomena, which threat the environment and people.

Nature of structural health monitoring programs depends on the functions of building and their age, size and configuration, connecting structures, environment conditions, available design data, etc. These surveys can be divided into several stages: preparation, detailed survey and analysis/identification. At the preparation stage the available information are collected and damaged structure areas are identified, which are photographed and shot on camera, the nature and scope of the damage is described. Design, construction and repair, operation documents are examined as well as the results of interviewing of persons involved in the above mentioned processes. An investigation program is prepared, in which requirement and scope of expertise work is studied. At the detailed investigation stage structure defects and their evolution are ascertained; the environment impact is characterized; form and dimensions of the structure are established; materials and their physical mechanical properties are identified; fixation conditions and loads affecting in standard and emergency loading cases are established; identification of nature, size and causes of damage and defects is performed; deflections, deformations, spectral response characteristics under operating and experimental loads are measured. At the analysis/identification stage a substantial description of the structural safety in short-term and long-term operation period is made [11-26].

Reliability of the structural health prediction depends critically on results of all stages of structural health monitoring program. Conclusions on the structural health can accurately match the reality, when damage, deformations and their causes are measured correctly. Also, the, mathematical models should well correspond to the real structure and should be properly applied to the provided lifetime of the structure.

2. Numerical models of structures

Parallel analysis algorithms and methods allow quick processing of a large amount of data and apply favorable conditions to expand nondestructive diagnostics of structures and evaluation of their condition. Those are successfully applied in complex transport and civil engineering structures. However due to approximate nature of numerical methods and uncertainty of data, the estimation of results should be carefully.

Causes of discrepancies between experimental results and numerical estimations of theoretical model can be different, among which more significant are the following:

- model structural errors, which can occur due to difficulties in specifying inhibition, connections, welding seams, edges, etc.,
- model algorithm errors, which can occur due to difficulties in specifying geometrical and material nonlinearities, etc.,
- model parameter errors, which can occur due to difficulties in specifying material and load properties, nature, etc.,
- measurement methodology, instrumental and operator errors.

These and other aspects of compliance of numerical analysis and experimental research should be taken into account, and all accepted assumptions should be motivated and balanced. It is not a simple, yet a very important stage of the structural damage identification, during which a set of calibration procedures is performed. Accuracy of models can be done by direct and inverse methods [19-25].

By direct solving a response to changes of initial parameters – geometry, material properties, supports and loads – is received. Due to these reasons stiffness and inertia properties of structure are changed, which results in changing of the nature of deformations and spectrum of dynamic response.

When solving the inverse task the experimental data are tried to bring together with the results of theoretical calculations by changing parameters of the structure. This solution is made by iterations, and structural areas and elements that are damaged (bear altered properties) are found. In this way the experimental measurements and analytical results can be identified.

The solution of inverse task requires significantly more efforts, whereas uncertainty of model parameters, just like errors of experimental measurements, has critical impact on evaluation results. Prediction of structural damages and their locations is performed by solving an inverse task according to a selected conformity criterion. It means that one should specify such a set of parameters, in the presence of which the selected criterion obtains the required value. The norm of resultant load vector can be used for such a criterion in static and dynamics tasks:

$$\Delta = \frac{\sum \left| \boldsymbol{M}\ddot{\boldsymbol{Q}} + \boldsymbol{C}\dot{\boldsymbol{Q}} + \boldsymbol{K}\boldsymbol{Q} - \boldsymbol{F} \right|}{\sum \left| \boldsymbol{F} \right|}$$

where $\boldsymbol{M}$, $\boldsymbol{C}$, $\boldsymbol{K}$ are mass, damping and stiffness matrixes, $\ddot{\boldsymbol{Q}}, \dot{\boldsymbol{Q}}, \boldsymbol{Q}$ are acceleration, velocity and displacement vectors, $\boldsymbol{F}$ is external load vector.

A solution scheme for prediction of structural damages can be defined by the following stages:

- preparation of a numerical model of the structure and its calibration performed on measurement results,
- measurements of the structure with defects are made in presence of static and dynamic loads,
- probabilistic estimations of the degree and location of structural damages.

Compliance of the structure numerical model with its measurement results is achieved by selecting such a set of parameters of the numerical model, at which the compliance criterion is met. Global optimization algorithms are applied to this solution. Since numerical models of actual structures are characterized by a large number of degrees of freedom, therefore multiprocessor systems and parallel analysis algorithms are used to solve these tasks.

3. Identification of structural damages

The prepared structure damage identification methodology, algorithm and software were tested for beam and plate structures. Defects were initiated in the structures and drifts of such damaged structures were calculated, which were taken as the results obtained by measurements. Furthermore, applying the prepared methodology and considering that location of the defects is unknown, predictions of damaged locations were made. Finally the predictions were compared to distribution of the initiated defects.

Results of the identification of defects of the following structures are presented:

a) – statically loaded flat truss,
b) – dynamically loaded flat truss,
c) – statically loaded spatial frame,
d) – statically loaded floor.

The first task deals with a flat truss, rigidity of beams of which stretching-compression in the damaged beams was reduced. Rigidity of all remaining beams is equal. The truss is supported at ends and is loaded by a force concentrated in the center. Deflection measurements are presented in all points of the truss. Deformation nature of the damaged truss, the calculated probability of beam damage and the initiated damages are shown in Fig. 1, in which the initiated damages (90% reduction of stiffness) are shown in gray, whereas those predicted – in dark.

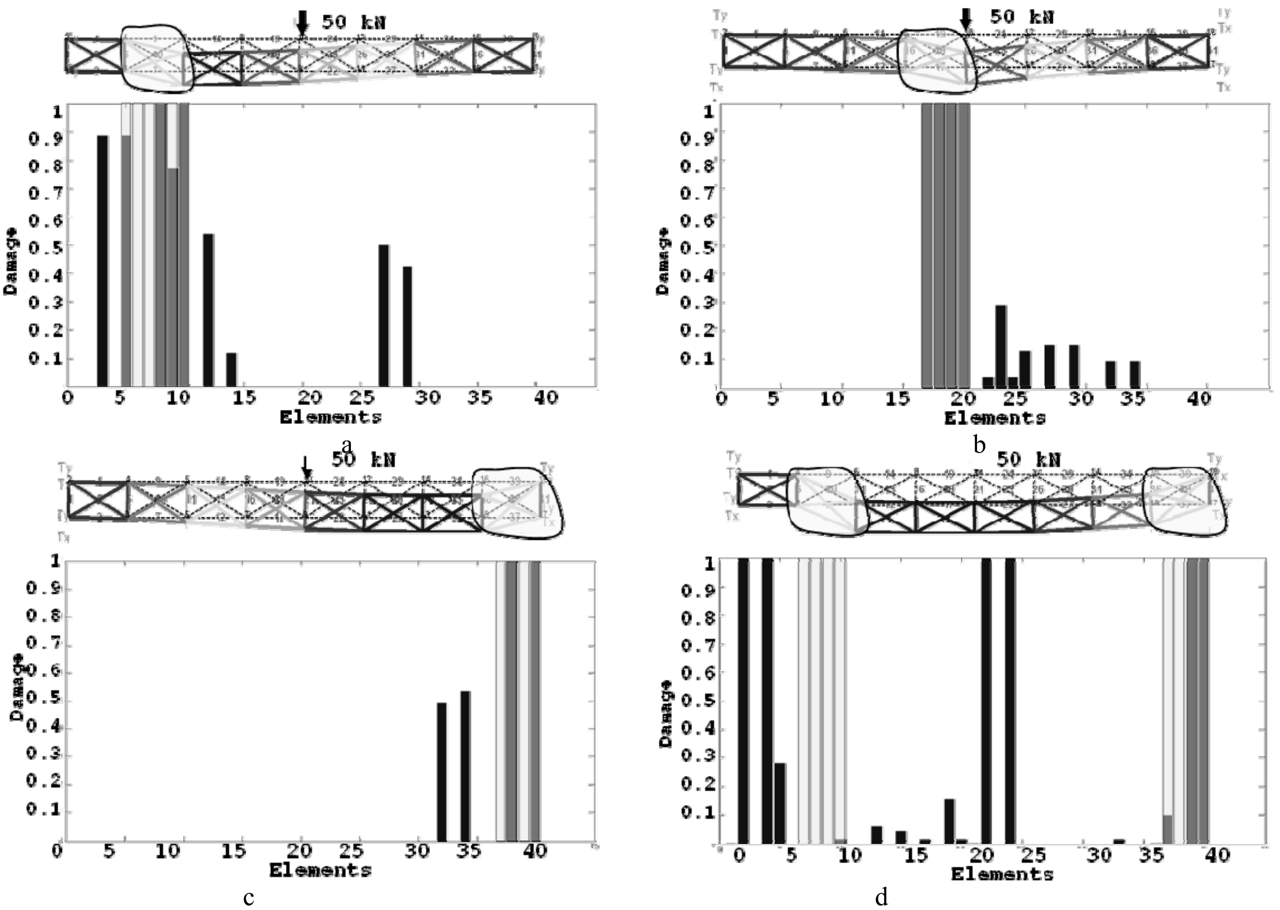


Fig. 1 Damaged truss deformations and comparison of matching the predicted defects with the initiated ones in different locations of the truss: a, c and d - near support; b – in the middle region

The second task dealt with the same structure as in the first task, however the force was time-dependent, as shown in Fig. 2, a. Force applied deflection point dependence on time with indicated damage is demonstrated in Fig. 2, b. The initiated damage here were spread over and distributed in elements 2, 4, 6, 8, 10, 20, 40. Estimated beam damage probability is shown in Fig. 2, c. Postulated (initiated) damages are marked in yellow, whereas those predicted – in blue.

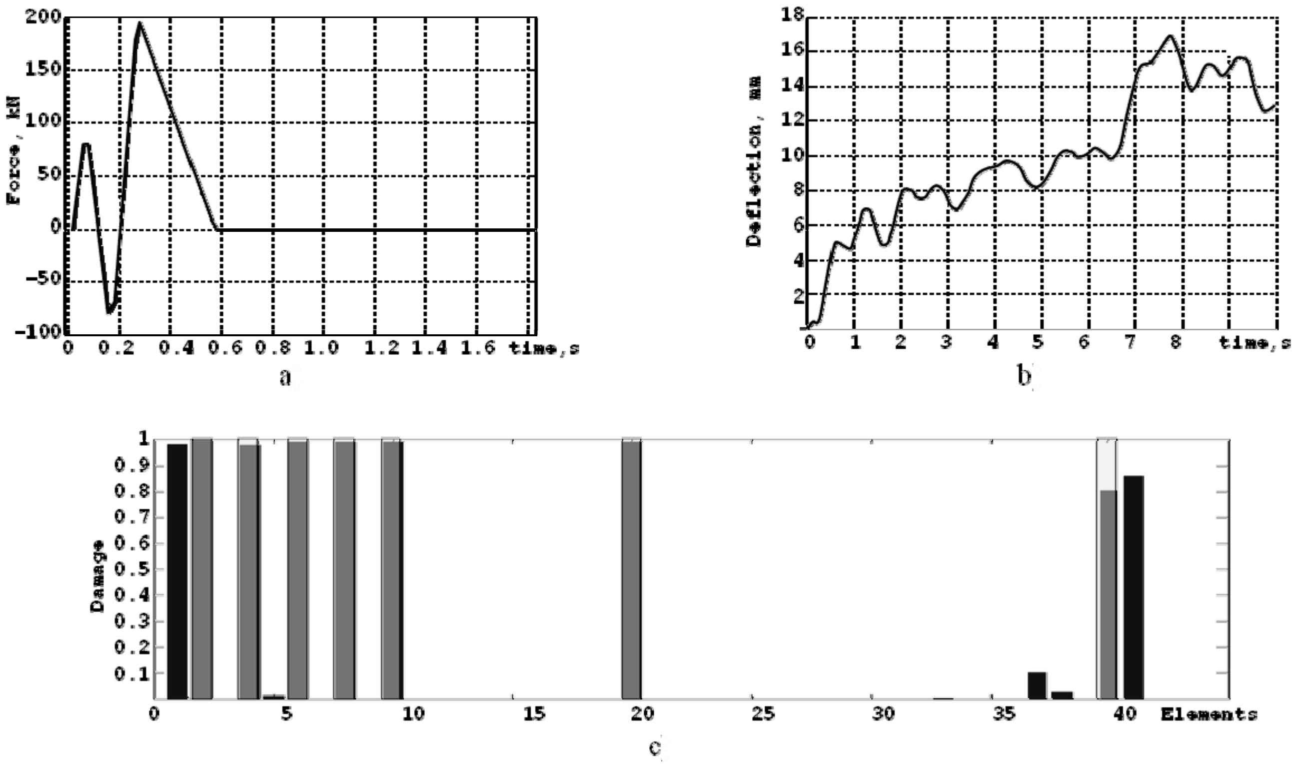


Fig. 2 Dependence of force (a) and its point of application (b) on time, and comparison of initiated and predicted damages (c)

The third task deals with a spatial frame, which geometry, fixations and loads, as well as initiated defects in elements 80-90 and 120-140 are shown in Fig. 3, a. The frame is loaded by a static force applied in the center and is firmly fixed in corners. Probability of damage of the frame elements is compared with initiated defects in Fig. 3, b.

These tasks were solved using unique developed software, applying which finite element models were formed, structure stress and deformation state analysis was performed, visualization and evaluation of results was presented. To this purpose MATLAB procedures library was used.

Actual civil engineering structures are usually mixed – they have beam, plate and block elements installed. If it is impossible to analyze the structure elements separately and becomes necessary to compose complex numerical models, then universal structure analysis systems, e.g. ALGOR, ABAQUS, ANSYS, etc. can be used, which offer large libraries of elements, materials and loads. Best results can be achieved when unique software is combined with universal systems because it significantly expands variety of analyzed tasks.

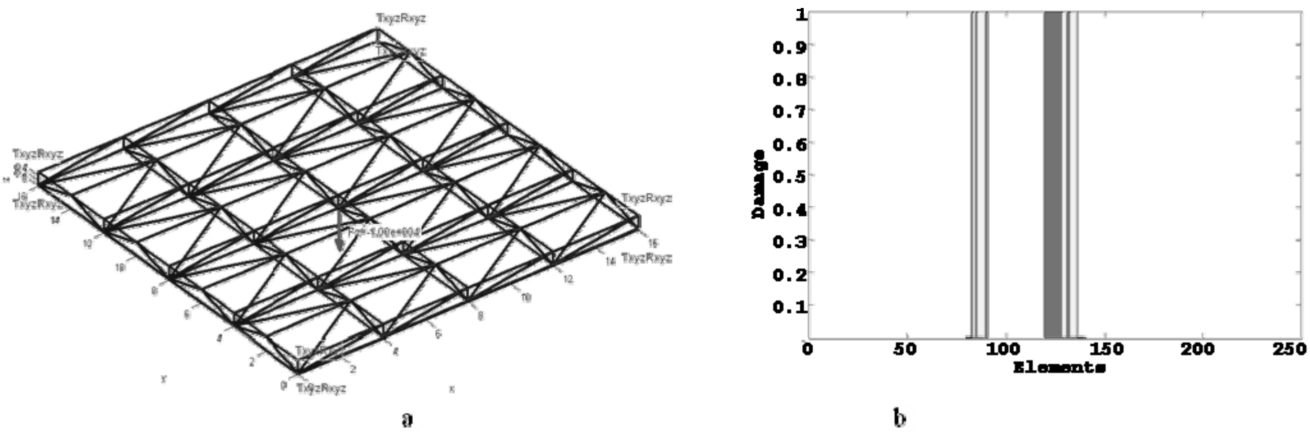
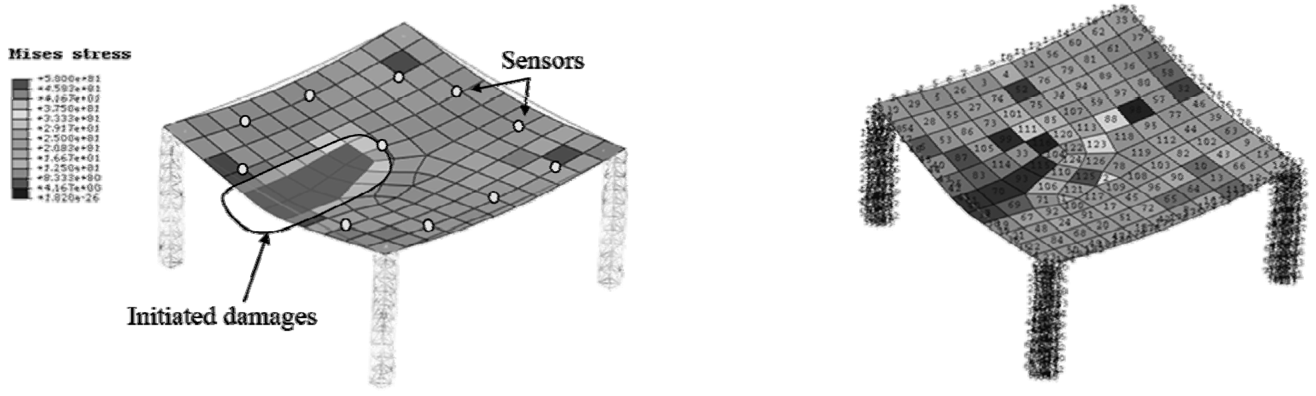


Fig. 3 Spatial frame finite element model, fixation, loads, initiated defects (a) and compliance of predicted defects with initiated ones (b)

The presented below fourth task analyzes the structure in which plate finite elements are used for the ferroconcrete, and beam finite elements are used for the pillars. The structure finite element model, initiated damages and locations of distribution of measurement sensors are shown in Fig. 4,a. Shift of the Mises stresses of the damaged structure in the floor is illustrated in Fig. 4,a, and that of the structure with predicted damages – in Fig. 4,b.



a b

Fig. 4 Deformations and stresses of a mixed structure building with initiated defects (a) and estimated defects (b)

According to these results it can be stated that by applying the proposed damage identification methodology, location and size of the predicted damages correspond to the initiated damages, and the degree of such correspondence depends on a chosen prediction methodology and quality of initial data (properties of the model, accuracy of measurements, methods of prediction). It should be noted that the damage search applied herein did not use initial solutions, which make the search process significantly more accurate and quicker.

4. Conclusions

It is noticed that success of the structure damage identification depends on reliable results of separate stages: measurements, structure modeling and prediction methodologies, equipment and personnel, and in order to reduce risk of errors reliable procedures of operations' checking should be provided for.

Algorithms and the unique software have been prepared designated for the solution of static and dynamic tasks of flat and spatial beam, shell and block structures using the finite element method, which can be applied to needs of structure strength prediction.

Several tasks for illustration purposes have been presented to demonstrate the possibilities of estimation of damage locations and risk probabilities applying both unique and universal software.

It has been noted that the applied methodology, algorithms and software identify well damage of beam and complex structures under stationary and variable loads and can be applied for practical purposes.

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KONSTRUKCIJŲ PAŽEIDIMŲ MATAVIMAI IR PROGNOZAVIMAS

R e z i u m ė

Straipsnyje nagrinėjami konstrukcijų pažeidimo nustatymo metodai, pagrįsti skaitinio modeliavimo ir deformacijų monitoringo rezultatais. Pasiūlytas atvirkštinis deformuojamų kūnų mechanikos uždavinio sprendimo būdas, apibrėžiantis konstrukcijos mechaninę būseną pagal jos apkrovimo ir deformavimosi pobūdį. Pateikta strypinių ir plokščių konstrukcijų su inicijuotais defektais pažeidimų prognozavimo pavyzdžių. Gauti rezultatai sudaro prielaidas kurti diagnostikos algoritmus.

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MONITORING AND PREDICTION OF STRUCTURAL DAMAGES

S u m m a r y

This paper presents the investigation of structural damage identification methods based on results of numerical modeling and deformation monitoring. Solution of deformed body mechanics task by contradiction describing the structure mechanical condition according to its loading and deformation nature is proposed. Examples of damage prediction in beam and plate structures with initiated defects are presented. The received results provide the basis for the development of diagnostics algorithms.

К. Пяткявичюс, В. Волковас

МОНИТОРИНГ И ПРРОГНОЗИРОВАНИЕ СТРУКТУРНЫХ ПОВРЕЖДЕНИЙ

Р е з ю м е

В настоящей работе приведено исследование структурных методов идентификации повреждений, основанных на результатах числового моделирования и мониторинга конструкций. Решение обратной задачи механики деформируемых тел заключается в описании структурных характеристик и условий нагружения и деформирования. Представлены примеры прогнозирования повреждений в стержневых и массивных конструкциях с инициированными дефектами. Полученные результаты обеспечивают основание для развития алгоритмов диагностики.

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