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INVESTIGATION OF STRUCTURES BY SIMULATION TECHNIQUES

Design, technology, reconstruction

New scientific results of the PhD thesis

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1. INTRODUCTION

Nowadays the computer simulation techniques are going to play very important role in the everyday engineering practice. Applying the simulation techniques there are several possibilities to solve different engineering and architectural problems. The development of the computer programs and hardware give adequate support for this important work. During my work I investigated some engineering problems in the view of computer simulation:

- applying Monte-Carlo simulation method in the design of structures
- simulation of the formation procedure and the load bearing capacity of the bars
- refurbishment of ancient masonry structures by lateral confinement

From the viewpoint of design practice, the current procedures for reliability assessment of structural components and systems contained in specifications do not fully utilize the potential of available computer technology. Monte Carlo Simulation (MCS) may play a significant role in the evaluation of data available from different sources including experiments, the experience and estimates furnished by the designer, the user, and others involved. Simulation, using MCS, is a very powerful and convenient tool for the analysis of load effect combinations, for determining resistance, for evaluating the probability of failure of structures and structural components, and for assessing serviceability criteria.

Furthermore at the engineering practice the most often applied designer softwares are based on FEM (finite element method) or FSM (finite strip method) methods. The theoretical mechanics and mathematics give the basis of these programs, and are very useful in the structural design. During my work I applied such programs, the so called ABAQUS and AXIS programs for the structural simulations.

2. APPLIED METHODES

2.1 Design of structural elements applying Monte-Carlo method

The MCS method directly determines the probability of failure corresponding to any combination of variable loads effects S, and the random variable resistance R. A personal computer creates tens of thousands of dots representing the possible interactions of resistance R and load effect S. To obtain the probability of failure, the number of dots in the Failure region, which appears to the right of the Failure Boundary line, is divided by the total number of dots. These results are then compared to the acceptable level of probability of failure.

Professor Pavel Marek was the coordinator of TERECO project, where the candidate and the supervisor were partners. A textbook and totally five computer programs (including M-Star™ and AntHill™ programs) were developed to help the reader in exploring the power of the simulation-based reliability assessment procedure. All five programs are based on the simple random sampling Monte Carlo simulation.

The computer programs allows solution of equations (algebraic, logarithmic, exponential and trigonometric) containing up to 30 random variables expressed by bounded histograms. The MCS method and the computer programs are applicable for problems related to the determination of resistance, combination of load effects, probability of failure, accumulation of damage and assessment of serviceability. The proposed procedure is also applicable to selected second order analysis problem such as column buckling. Problems involving two- and multi-component variables can be analyzed using ”anthill” method. Selected special problems such as principal stresses resulting from multi-component structural response to several loadings from different sources can be solved.

Several engineering design problem can be calculated such as safety of truss-girder bar, safety of a rectangular hollow section, safety of columns in a frame, safety of the tee joint of a welded I-section, safety of a bolted splice, etc. Moreover the MCS method can be applied to produce the buckling curve of a welded I-sectioned beam.

The MCS method still not very applicable for the real design practice, but I have shown the design potential of this simulation technique.

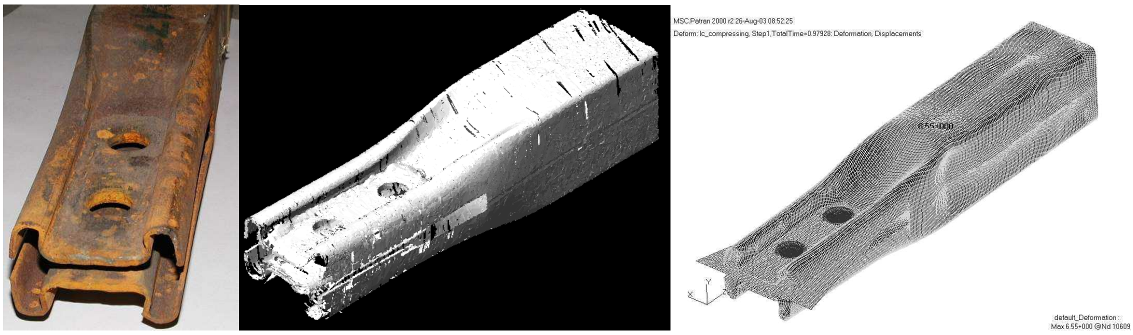
2.2 Structural modelling by applying ABAQUS simulation

For numerical simulations I applied ABAQUS program, which is based on FEM technique. It is applicable for modelling the producing process, the loading and unloading of structural elements, refurbishment and reinforcement of different structures, etc. During my work I applied ABAQUS in the following simulations.

2.2.1 Simulation of a special formation procedure

I performed a full-scale test on a steel space-truss, which contains uniform bars. The ends of the bars have special shape to ensure the adequate bolted connection at the joints. For the computer simulation I had to model the formation procedure of this special bars' ends. I visited the DUNAFERR Acélszerkezeti Kft. to see the shaping process, then I modelled the procedure by ABAQUS program.

A unique method was applied for the verification of numerical results: 3D laser scanning procedure. The MTA SZTAKI (Hungarian Academy of Sciences, Budapest) gave the possibility to examine the truss bars by a three-dimensional laser scanner. Until that time industrial designers used the 3D laser scanner and I was the first civil engineer, who used the scanner in structural engineering work. The simulation was excellent.



The real bar, the result of 3D laser beam scanning and the numerical model of the bar

2.2.2 Load bearing capacity of compressed bars

Numerical analyses of compressed bars were the next part of my work. These numerical analyses were performed by ABAQUS version 6.3-2 finite element program and for pre- and post-processing the MSC Patran 2000 r2 program was applied. The calculations were done at WOCO Gumitech Ltd., Budapest.

During the calculations I investigated the compressed bar under different load cases such as: concentrated normal force, pure bending moments around the x- and y-axes of the cross-section, pure torsional moment around the longitudinal z-axis, normal force with large eccentricity in both x and y direction and normal force with small eccentricity in one direction only. The small eccentricity was the tenth of the width of the bar.

The numerical results gave the behaviour and load bearing capacity at different load cases. The main result of this investigation was that the bars in a space truss has not perfectly centered and pinned connections, and secondary bending effect occur in the real trusses.

Numerical result of the compression with small eccentricity, the result of the full-scale experimental test and the digitalized result of the 3D laser scanner

2.2.3 Refurbishment of ancient masonry structures by lateral confinement

The refurbishment is very important tool to increase the life time of ancient structures. A very often applied method is reinforcing ancient masonry structures (walls, towers, buildings, etc.) by iron or steel lateral confinement. I performed an ABAQUS simulation series applying this method on masonry walls. The main goal of this simulation series was to find the effectiveness of the confinement in the load bearing capacity of the masonry wall. I modified different setup parameters: wall thickness, distance between the plate side, the area of confining plate, and calculated the increment of the load bearing capacity.

In case of nearly the same value of D_{plate}/T_{wall} ratios the possible increments of strength are nearly the same at the walls. This fact demonstrates one of the findings of *G. Ballio* and *G.M. Calvi*, that the ratio between the plate distance and wall thickness is a fundamental parameter during the design process of reinforcing. It can be conducted ? that it is important to limit the distance between plates' edge, while the ratio between plates' and bars' area can be maintained around the separator value ($A_p/A_b \approx 100$).

The most important effect of this strengthening technique is allowing stress redistribution without local collapse. At this method the properties of steel bars are fully exploited, either in terms of strength or in terms of energy absorption capacity.

2.3 Experimental analysis of structures

The next simulation technique to investigate the behaviour of structures is the full-scale or model experimental analysis of structures. The experiments are expensive, needs lots of preparations, precise execution and evaluation, and the independent control is very important to avoid the rough errors. The experiments help us to calibrate the numerical analyses, and to perform parametrical investigations without real experiments. During my work I performed the following experiments.

2.3.1 Verification of experimental buckling curves

The lateral buckling design curves of beams are based on experiments in the design codes, like for example in Eurocode series. The MCS method can be applied to present the design curve on the basis of fully probabilistic method. My examination deals with the lateral buckling behaviour of a welded, steel, I-sectioned, simple supported beam.

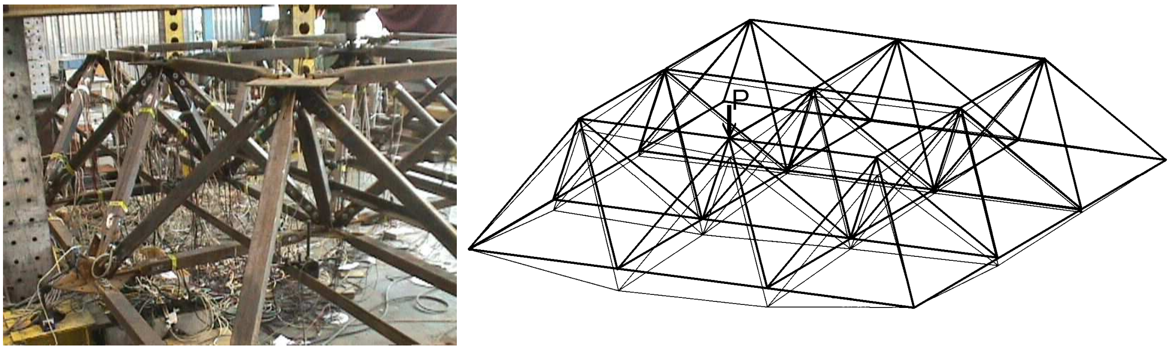
The calculations made on the basis of the theoretical solution of differential equation, taking into account the experimental results performed in different countries.

The computer simulation was done by M-Star™ program. During the computer simulation the length of beam was changed, and the corresponding critical bending moment were calculated 100 000 times in each case, and the results were evaluated statistically. The AntHill™ program was used to evaluate directly the simulated lateral buckling curve.

2.3.2 Full-scale experiments on the space-truss and the component bars

As I mentioned in Chapter 2.2.1, I performed a full-scale test on a steel space-truss, which contains uniform bars. The experiments were done in the Structural Laboratory of the BUTE Department of Structural Engineering. The preparation took one year; the experiments needed two months and the evaluation more several months. I prepared three experiments on the steel space truss segment and performed 375 digital measurements on strain gauges, inductive transducers and the loading hydraulic jacks at every load step. After the disassembly of the collapsed truss, I investigated 16 bars in individual compression tests. The numerical simulations of these experiments were done by AxisVM10 FEM program.

During the calibration of the numerical models I took into account the semi rigid effect at the bolted connections. The secondary bending moment can be demonstrated by the results of the strain gauges. Applying the verified numerical model I got the possibility to perform virtual experiments without real specimens.



The examined space-truss roof-system segment and the deflection of the first experiment

2.3.3 Virtual experiments on confined masonry walls

The calibration of the numerical models of confined masonry walls were based on full-scale test series. These experiments were done by G.Ballio and G.M.Calvi in Pavia, Italy. From the results of these experiments, I obtained lots of parameters, to create a good numerical model by ABAQUS program. The applied parameters from the documentation of the test series are the following: the type of failure modes (yielding of the horizontal bars, punching of masonry underneath the confinement plates, shear-tensile failure of masonry in the less confined zones between plates); the geometrical data of the walls, steel bars and confining plates; the number of the confining plates; the material properties of the masonry walls and the steel members (yield strength, Young's modulus, stress-strain curves, etc.).

Applying the experimental parameters I modelled the test series and obtained a numerical model, which is applicable to perform further virtual experiments on masonry walls with lateral confinement.

3. NEW SCIENTIFIC RESULTS

3.1 New result 1: Simulation applying Monte-Carlo method

a) buckling curves

I applied Monte-Carlo method for modelling the lateral buckling behaviour of a welded I-sectioned simple supported beam. The examination was done on the basis of an ideal model. The beam is under uniform bending moment. The assumed distribution of the geometrical data (the widths and thickness of plates and the length of beam) are Gaussian probability density function. During the computer simulation the length of column was changed, and the corresponding critical bending moment were calculated. Thus I produced the buckling curve of that welded I-sectioned beam.

Related publications: [1], [2], [8], [11],

b) structural elements

I applied Monte-Carlo method for calculating the safety of different structural elements. The calculated problems were typical structural exercises such as:

- safety of a truss-girder bar subjected to tension
- safety of a rectangular hollow section exposed to multi-component loads
- safety of a column in a frame
- safety of the tee joint of a welded I-section
- shear resistance of a bolted beam to beam connection

During this calculation I showed the potential of the Monte-Carlo method in the engineering practice, and pointed out the possible advantage against the design codes.

Related publications: [1], [2], [4]

c) buckling behaviour of a steel frame

I applied Monte-Carlo method in a parametrical examination at a single beam-column frame. During the calculations the lengths of column and beam were changed and the corresponding critical buckling intensity of distributed load of the column was calculated.

Elastic and 2^{nd} order analysis was applied, thus the axial force effects are taken into account by stability functions.

As the result of the calculations the buckling surface of column was produced with the critical intensities of distributed load.

Related publications: [1], [2], [4], [8], [11],

3.2 New result 2: Simulations of Producing and Design Structures

a) simulation of the formation procedure of the bars

On the basis of the producing process, I investigated a numerical model of the formation procedure of the bars. I had to model the formation process to obtain the real model of flattened bar ends. The formation takes effect just at the end of the bars. Therefore I decided to model only a part of the bar, near the flattened end instead of the whole member. Furthermore it is decided to model only the quarter of the hollow cross section and the half of the pressing tool due to the symmetry of the members and the formation process. The loading was displacement controlled.

I applied a new method for the verification of the result of the numerical analysis, a 3D laser scanner. I verified the numerical model with good coincidence.

Related publications: [6], [7], [13], [14], [15], [16], [17]

b) numerical analysis of compressed bars

I created the numerical model of the whole bar applying the resulted shape of the quarter bar model of the ″flattening″ process. I performed several loading on this model to find out the real behaviour of the built up truss members. The applied load cases were:

- concentrated compression force
- pure bending moment in both direction
- pure torsional moment
- normal force with two bending moments (large eccentricity)
- normal force with small eccentricity

The small eccentricity was the tenth of the width of the bar. I get the best solution of the truss bars with the last loading model, the small eccentricity.

I verified the numerical results of the whole bar model with the comparison of my experiments on individual bars.

Related publications: [3], [5], [6], [7], [9], [10], [12], [13], [14], [15], [16], [17]

c) numerical analysis of the steel space-truss

I created the numerical model of the investigated steel space-truss. The model contains special connections at the joints, which take into account the semi-rigid effect of the secondary bending moments. This model is applicable to present the three full-scale experiments.

- eccentric concentrated force on the top side joint in the elastic range
- concentrated force on the top mid joint in the elastic range
- concentrated force on the top mid joint until collapse

Applying this model I can calculate other special load cases on this space truss without real full-scale experiments.

Related publications: [3], [5], [6], [7], [9], [10], [12],

3.3 New result 3: Refurbishment of ancient masonry structures

a) numerical simulation of the lateral confinement

I investigated some numericals model for the lateral confinement reinforcing technique of ancient masonry walls. Allowing for the symmetry of both geometry of the model and loading action, only the eighth of the entire masonry has been considered for the computer analysis. The main geometrical and material parameters, such dimensions of masonry wall, numbers of reinforcing bars, material behaviour of the masonry, etc. came from the performed experiment series.

Corresponding to the above mentioned parameters, the calculated behaviour was that as was in the experiments.

Related publications: [18]

b) parametrical analysis series applying lateral confinement

Parametrical analysis series were performed applying the lateral confinement reinforcing procedure. I get designing directives to determinate the effect of the reinforcing by computer simulation without experiments.

During the parametrical analysis series I applied different wall thicknesses, plate sizes and thicknesses, and gave design role for the effectiveness of lateral confinement.

In case of nearly the same value of D_{plate}/T_{wall} ratios the possible increments of strength are nearly the same at both of walls. This fact demonstrates that the ratio between the plate distance and wall thickness is a fundamental parameter during the design process of reinforcing

Related publications: [18]

4. RELATED PUBLICATIONS

Book, sections in book

[1] Dr. Iványi Miklós – Fülöp Attila, szerkesztők: *Acélszerkezetek szimulációs vizsgálatai megbízhatósági eljárással - Examination of Steel Structures using Simulation-based Reliability Assessment (SBRA-method)*, Műegyetemi Kiadó, Budapest, 2001, ISBN 963 420 680 8, p.286

[2] Marek, P., Brozzetti, J. and Gustar, M. editors: *Probabilistic Assessment of Structures using Monte Carlo Simulation*, TeReCo Product, ITAM CAS CR, Prague, 2001 June, ISBN 80-86246-08-6. (14 mintapélda nyomtatásban további 21 mintapélda a CD mellékleten A. Fülöp – M. Iványi szerzői név alatt 5 különböző fejezetben)

Paper in collected volume

[3] Fülöp A., Iványi M. *Acél térrácsos tetőszerkezet kísérleti vizsgálata*. Tassi Géza, Hegedűs István, Kovács Tamás, szerkesztők: A Budapesti Műszaki és Gazdaságtudományi Egyetem Építőmérnöki Kar Hidak és Szerkezetek Tanszéke Tudományos Közleményei, Halász Ottó születésének 75. évfordulója alkalmából, Műegyetemi Kiadó, Budapest, 2002, HU ISSN 1586-7196, p. 37-42.

[4] Dr. Iványi M., Fülöp A. *Acélszerkezetek szimulációs vizsgálatai*. Bársony János szerkesztő: Tartószerkezeti kutatások. Évfordulós kötet Lenkei Péter tiszteletére, Pécsi Tudományegyetem Pollack Mihály Műszaki Főiskolai Kar, Pécs, 2003, pp. 37 – 43.

International journal paper

[5] Fülöp A., Iványi M. *Experimentally Analyzed Stability and Ductility Behaviour of a Space-Truss Roof System*. International Journal of Thin-Walled Structures, Elsevier Science Ltd, February 2004, Vol 42, pp. 309-320., ISSN: 0263-8231, IF: 0.517 L E URL: http://authors.elsevier.com/sd/article/S0263823103000624

Domestic journal paper

[6] Fülöp Attila, Iványi Miklós *Acél térrács kísérleti és numerikus vizsgálata*. MAGÉSZ – Acélszerkezetek különszám, 2004, ISSN 1785-4822, pp. 37-40.

[7] Fülöp Attila Acél térrács rúdjainak numerikus vizsgálata és kalibrálási lehetőségei. MAGÉSZ – Acélszerkezetek, III. évfolyam 1. szám, 2006, ISSN 1785-4822, pp. 50-53

International conference paper

[8] Fülöp A., Iványi M. *Computer Simulation of the Buckling Curves for Steel Structures using Monte-Carlo Method* In: Li Hyung Lee, Ginsztler János, editors, Proceedings of the 3rd Korean-Hungarian Symposium on "New Methods in structural engineering", (organizer: Hungarian Academy of Engineering), Budapest, Hungary, 2001. June 22., Seoul, KAIST, 2002

[9] Fülöp A. *Effect of semi-Rigid Joints of Space-Truss Steel Structures*. In: Peter Schießl, Norbert Gebbeken, Manfred Keuser, Konrad Zilch, editors, Proceedings of the 4th Ph.D.Symposium in Civil Engineering, Munich, Germany, September 19-21, 2002. Springer-VDI-Verlag GmbH & Co.KG, Düsseldorf, 2002, Volume 1, ISBN 3-935065-09-4, pp. 169-177.

[10] Fülöp A., Iványi M. *Full-Scale tests of a Space-Truss Roof System*. In: Iványi Miklós, editor, Proceedings of the Stability and Ductility of Steel Structures, Professor Ottó Halász Memorial Session, September 26-28. 2002, Budapest, Akadémiai Kiadó, Budapest, 2002, ISBN 963 05 7950 2, p. 387-393.

[11] Fülöp A., Iványi M. *Computer Simulation of the Buckling Curves for Steel Structures Using Monte-Carlo Method*. In: Iványi Miklós, editor, Proceedings of the Stability and Ductility of Steel Structures,

Professor Ottó Halász Memorial Session, September 26-28. 2002, Budapest, Akadémiai Kiadó, Budapest, 2002, ISBN 963 05 7950 2, pp. 119-126.
[12] Fülöp A., Iványi M. *Full-scale tests of a space truss roof system*. In: Jármai Károly and Farkas József, editors, Metal Structures: Design, fabrication, Economy, Proceedings of the International Conference on Metal Structures – ICMS-03, Miskolc, Hungary, April 3-5, 2003, Millpress Rotterdam Netherlands 2003, ISBN 90 77017 75 5, pp. 93 – 97.
[13] Fülöp A., Iványi M. *Buckling Modes of Flattened Edges Rectangular Hollow Members*. In: B.H.V. Topping, editor, Proceedings of The Ninth International Conference on Civil and Structural Engineering Computing, 2-3 September 2003, Egmond-aan-Zee, The Netherlands, Civil-Comp Press, Stirling, Scotland, 2003, pp. 105-106 + CD-ROM: Paper 42, 10 pages, ISBN 0-948749-87-3 book, ISBN 0-948749-88-1 CD, ISBN 0-948749-89-X combined set.
[14] Fülöp A., Iványi M. *Coupled Buckling Modes of Rectangular Hollow Members*. In: M. Pignataro, J. Rondal and V Gioncu, editors, Proceedings of the Fourth International Conference on Coupled Instabilities in Metal Structures, CISM 2004, Rome, Italy, 27-29 September 2004, Editura Orizonturi Universitare, Timisoara, 2006, pp. 191-202, ISBN 10: 973-638-268-0, ISBN 13: 978-973-638-268-0.
[15] Iványi M, Fülöp A. *Buckling Behaviour of Rectangular Closed Cross Sectional Members*. In: Dan Dubina and Daniel Grecea, editors, Recent Advances and New Trends in Structural Design, International Colloquium Dedicated to the 70th Anniversary of Professor Victor Gioncu, Editura Orizonturi Universitare, Timisoara, 2004, ISBN 973-638-119-6, pp. 155-164.
[16] Fülöp A., Iványi M. *Numerical Analysis of the Buckling Behaviour of Rectangular Hollow Members*. In: B.H.V. Topping, C.A. Mota Soares, editors, Proceedings of The Seventh International Conference on Computational Structures Technology, 7-9 September 2004, Lisbon, Portugal, Civil-Comp Press, Stirling, Scotland, 2004, pp. 347-348 + CD-ROM: Paper 156, 10 pages, ISBN 0-948749-93-8 book, ISBN 0-948749-94-6 CD, ISBN 0-948749-95-4 combined set.
[17] Fülöp A., Iványi M. *Buckling Analysis of Space-truss Roof System. Experimental and Numerical Investigations*. In: B. Hoffmeister, and O. Hechler, editors, Proceedings of the Fourth European Conference on Steel and Composite Structures, Research-Eurocodes-Practice, EUROSTEEL 2005, Maastricht, The Netherlands, June 8-10, 2005, Druck und Verlagshaus Mainz GmbH, Aachen, 2005, Volume A, pp. 1.2-155 – 162, ISBN 3-86130-812-6.

Technical Report

[18] Fülöp A. *Strengthening of masonry structures by lateral confinement* In: Iványi M., Hegedűs L., editors, Refurbishment of Structures, Report, TEMPUS S_JEP 09524-95 Use of Steel in Refurbishment, as an Environmentally Friendly Activity, Budapesti Műszaki Egyetem, Acélszerkezetek Tanszéke, 1997, pp. 83-96., ISBN 963-421-549-1