USING NUMERICAL MODELS FOR THE ANALYSIS OF STRUCTURAL FAILURES

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ABSTRACT

The number of publications referring to case studies on structural failures has considerably increased in recent years. The Journal of Performance of Constructed Facilities (published by the American Society of Civil Engineers, or ASCE) publishes papers that examine the causes and costs of construction failures and other performance problems. A rise has recently been detected in the number of papers dealing with cases of structural failures analysed by numerical models. For example, in 2013, the Journal published a special issue containing a compilation of cases of interest in this field in which the failures had been studied by means of advanced numerical models.

Numerical models are being increasingly used to simulate the behaviour of damaged structures. These models can predict failure events by the analysis of: non-linear behaviour of materials, buckling, large displacements, inter-surface contact, cracking, etc.

This paper contains a review of the most frequently used numerical simulation techniques for structural failures in a collection of case studies. Separate treatment is given to steel, concrete, timber and masonry structures. Attention is also paid to potential problems due to soil-structure interactions. The aim is to make researchers and practitioners aware of the possibilities offered by advanced numerical models for the study and diagnosis of damaged structures.

1. INTRODUCTION

The study of structural failures is doubly important: on one hand, it provides a diagnosis that makes it possible to find out the causes and extent of the damage and so determine the corresponding responsibilities, and on the other the analysis of actual failures is a means of learning how to improve future designs. It should be remembered that human beings have always learned to build by trial and error.

The study of these failures has become even more important in recent years and many papers have been published in scientific journals. A search of Scopus using the terms given below revealed 1851 papers on failures in real structures:

1. Article title, abstract, keywords: structure, failure, “case study”
2. Subject area: engineering
3. Document type: article

Figure 1 shows the number of papers published each year for the last 20 years using the above terms and is a clear indication of the growth of interest in this field.

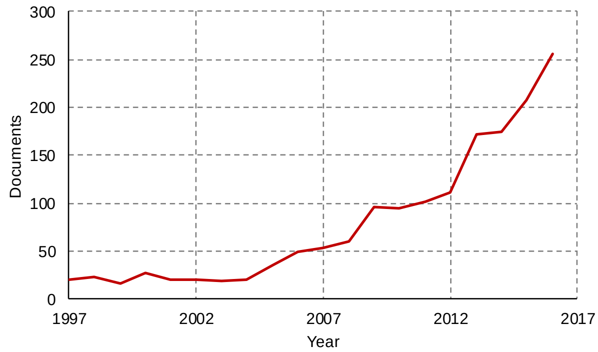

Figure 1. Papers referring to studies on actual failures published in Scopus indexed journals.

There are now a number of scientific journals dedicated to the study of failures and the assessment of existing structures, including: Journal of Performance of Constructed Facilities (American Society of Civil Engineers, or ASCE), Engineering Failure Analysis (Elsevier) and Proceedings of the ICE - Forensic Engineering (Thomas Telford). In addition, congresses on the same subject are frequently organised, such as those by the ASCE and ICE (Institution of Civil Engineers, United Kingdom).

The development and improvement of new numerical simulation techniques, together with the increased capacity of today’s computer programs, has led to higher use of these methods to study failures and assess the condition of existing buildings.

This paper contains the experiences of authors as editors and associate editors of the Journal of Performance of Constructed Facilities (JPCF). Section 2 contains information on papers published in this journal using numerical simulations. Section 3 contains a summary of a special issue of the journal dedicated to case studies using numerical models. Section 4 deals with case studies that were based on three of the most widely used simulation tech-

niques at the present time.
The aim of this article is to make researchers and practitioners aware of the possibilities offered by numerical models for the study and diagnosis of damaged structures.

2. NUMERICAL MODELLING IN THE JOURNAL OF PERFORMANCE OF CONSTRUCTURED FACILITIES

The JPCF is published by the American Association of Civil Engineers (ASCE) and sponsored by the Forensic Engineering Division. The journal is published six times a year. Since being founded in 1987 by Kenneth L. Carper, a total of 1355 papers have been published, e.g. in 2014, 100 papers were published, in 2015 175, and in 2016 the number increased to 212.
The JPCF is indexed in the JCR. Its impact factor is 1.192, occupying the second quartile (Q2) in the category “Construction and Building Technology”.
The aims and scope of the journal can be consulted at: http://ascelibrary.org/journal/jpcfev, and are as follows:
“The Journal of Performance of Constructed Facilities attempts to improve the quality of the constructed product through interdisciplinary communication. Papers examine the causes and consequences of failures and other performance problems.
The principal purpose of the Journal is to disseminate information on failures and performance deficiencies of constructed facilities. The term “failures” in this context may mean catastrophic events, but also includes any performance deficiency from which a significant lesson can be learned, such as serviceability problems. Both the technical causes and procedural causes of failures are of interest. Procedural causes include human errors in design, construction, and/or operation that allow the failures to occur.
The Journal welcomes manuscripts that deal with failures, methods of investigation of failures, special techniques for failure investigations, reconstruction and repair, and issues of ethics.
Also of interest are manuscripts on design and construction practices that could lead to or have led to failures. Papers that discuss the interface between various professionals in the construction industry are of special interest. Manuscripts discussing risk management and failure prevention techniques are also encouraged. In addition, manuscripts on monitoring the performance of existing facilities and maintenance of the infrastructure are within the intended scope of the Journal.”
The number of papers published on failure analysis and structural assessments by numerical models has grown considerably in the last few years, as can be seen in Figure 2, which shows the papers published each year in the last 10 years, together with those based on numerical models.
The Finite Element Method (FEM) is the leading simulation technique employed, although others are now gaining ground, such as the Applied Element Method (AEM) and the Finite Difference Method (FDM).
Figure 3 gives the percentage use of the above three techniques in the papers published by the JPCF.

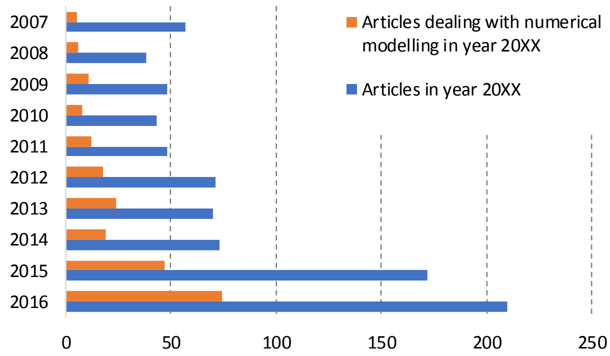

Figure 2. Papers published in the last 10 years in the JPCF: Total papers per year vs papers based on numerical modelling.

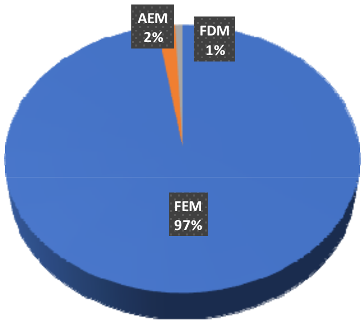

Figure 3. Percentage use of three numerical simulation techniques (FEM, AEM, and FDM) in papers published by the JPCF

3. SPECIAL ISSUE ON ANALYSIS OF STRUCTURAL FAILURES USING NUMERICAL MODELLING

Due to the growing importance of numerical modelling in the study of structural failures, the JPCF published a special issue in 2013 entitled “Analysis of Structural Failure Using Numerical Modelling”, with nine papers that analysed failures by numerical modelling. These included one by Bartoli & Betti (2013), who analysed the cracks found in the *Capella dei Principi* in Florence, Italy, including onsite surveys for subsequent nonlinear FEM modelling, which made it possible to reproduce the structure’s behaviour and thus arrive at the cause of the damage. This paper received the award for the best paper published by the journal in 2013. Figure 4 shows part of the numerical model.

Milani & Venturini (2013) analysed failure mechanisms in four masonry-built churches by means of numerical modelling with several unique characteristics, such as an analysis of the entire masonry structure, use of the homogenisation technique, and nonlinear behaviour.

Figure 4. Numerical simulation carried out by Bartoli & Betti (by courtesy of M. Betti).

Xu et al. (2013) studied the progressive collapse of stone arch bridges. Numerical simulation consisted of using three-dimensional FEM to perform a nonlinear analysis using contact algorithms in conjunction with the deactivation-element technique. The results obtained predicted the actual behaviour of stone arch bridges. This paper thus provided reference points for the analysis and prevention of progressive collapse in stone arch bridges.

Lourenço & Medeiros (2013) described the failure of a long-curved veneer wall, which exhibited significant out-of-plane movements shortly after completion, and which partially collapsed during the operation to dismantle sections of the veneer. The authors used FEM to clarify the causes of the collapse and to assist in planning the repair work.

Del Coz Díaz et al. (2013) used numerical modelling to determine the causes of the collapse of a masonry curtain wall in a factory attributed to wind action. An initial model was developed to consider fluid-structure interaction and determine the wind loads on the wall, using the loads thus obtained in an FEM simulation of the wall collapse. A view of the model can be seen in Figure 5.

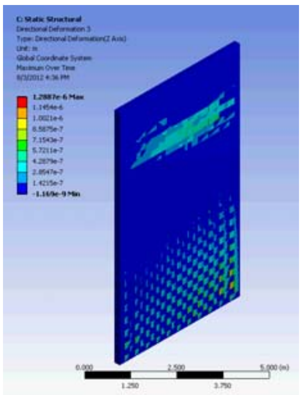

Figure 5. Model that simulated the behaviour of a wall subjected to wind loads (Del Coz Díaz 2013)

Augenti & Parisi (2013) analysed the collapse of a long-span steel roof that fell without any warning when still under construction. The authors carried out FEM simulations to determine the causes, including the possibility of structural buckling (see view of the simulation in Figure 6).

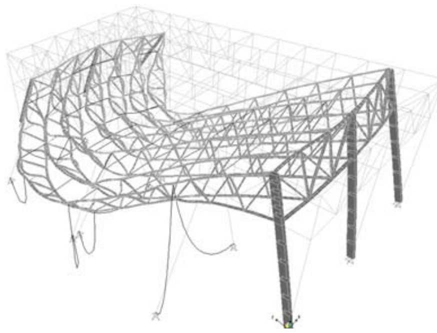

Figure 6. Simulation model of the collapse of a long-span steel roof (Augenti and Parisi 2013).

With a view to reproducing the catastrophic fire in 21 oil storage tanks in Puerto Rico in 2009, Batista-Abreu and Godoy (2013) simulated the behaviour of the oil tanks under a range of fire conditions. Their nonlinear analysis enabled them to establish the tanks' buckling failure modes and the most critical zones in relation to their behaviour in fires.
Ceci et al. (2013) studied the behaviour of irregular RC structures under seismic loads based on the effects of the 2009 earthquake in L'Aquila (Italy), using FEM and pushover analysis to determine the structures' ability to resist these loads.
Lee et al. (2013) described the numerical modelling of a highway dip slope slide, using two-dimensional limit equilibrium analysis to check the original design, together with three-dimensional finite-difference-element analysis to determine the most likely causes of the failure.

4. CASE STUDIES AND TECHNIQUES

As mentioned in Section 2, the simulation techniques used in the papers published in the JPCF are the Finite Element Method, Applied Element Method, and Difference Element Method. Below we give a brief description of each one, with references to studies in which they were used.

4.1. Finite Element Method

FEM is the most widely used method in the numerical simulation of structures and, as indicated in Section 2, was selected for most of the studies published in the JPCF.
The complexity level of the models covers a wide range, from elastic linear models for linear elements to highly complex models including non-linearities and solid elements. The latter type achieves close approximations to the actual structural behaviour, but at quite a

high computational cost, so that most studies resort to simpler models that combine linear and surface elements. In fact, in certain situations solid, surface and linear elements can be combined in a single model.

FEM has been used to simulate all types of structures (steel, concrete, timber and masonry) and to simulate soil-structure interaction. Some of these applications are briefly described below.

One of the leading studies in the field of RC structures, for example, is that by Çavdar and Bayraktar (2016) on a building that collapsed during an earthquake in Van (Turkey). Gu et al. (2017) analysed the collapse of a super-large cooling tower due to column failure. Vercher et al. (2015) studied the behaviour of slabs damaged by severe corrosion, while Wilcoski & Heymsfield (2002) used FEM to assess the behaviour of an airport control tower in an earthquake. Rajagopal and Kang (2016) used FEM to evaluate the damage and propose a repair plan for a coal storage yard.

FEM is also frequently used to analyse steel structures: Altunişik et al. (2017) studied the failure of a roof overloaded with snow. Lindquist et al. (2016) assessed the state of a bridge that had been retrofitted to withstand seismic forces. Laurendeau et al. (2015) assessed a steel bridge from models that had been previously validated by monitoring, and Augenti & Parisi (2013) analysed the collapse of a roof under construction.

Among the studies on masonry structures, those by Bartoli and Betti (2013) and Lourenço and Medeiros (2013) stand out (see Section 3). Mortezaei and Motaghi (2016) assessed the behaviour of a masonry tower under seismic loads in Iran. Other interesting work was done by Hejazi et al. (2016) and Yekrangnia and Mobarake (2016), who analysed 9 historical brick masonry minarets and a monastery, respectively, by FEM techniques. In another recent work, Bartoli et al. (2016) studied the magnificent dome of *Santa Maria del Fiore* in Florence, designed by Brunelleschi.

Timber bridges were the subject of an interesting study by Seo et al. (2016), who analysed the state of 11 bridges and then drew up a series of protocols that they subsequently verified by numerical models.

The combination of geotechnical and structural engineering is a particularly complex field when the soil-structure interaction is analysed. For example, Liu et al. (2017) and Chen et al. (2016) carried out two excellent studies involving a numerical simulation of the interaction of a tunnel with its surroundings, while Li and Guo (2017) analysed the damage in a residential building caused by expansive soil movement.

4.2. Applied Element Method

In AEM, a structure is simulated by an assembly of relatively small elements connected by springs at the points of contact between the surfaces of the elements. Normal and shear springs are responsible for the transfer of normal and shear stresses from one element to the next. AEM is an excellent tool for simulating processes with large displacements and rotations and can faithfully simulate cracking and collision of structural elements. The main advantage of this method is that it can track the structural collapse behaviour passing through all stages: the application of a load, initiation and propagation of cracks, and element separation until total collapse of the structure.

This method is being increasingly used to study progressive collapse, as in the studies by Helmy et al. (2013) and Khalil (2012). Salem et al. (2016) used AEM to simulate a bridge collapse, while Chehab et al. (2017) used it to analyse the behaviour of structures subjected to blast loading. As can be seen from the four cases described, the processes analysed include the need to simulate large displacements, rotations and inter-elements collisions.

4.3. Finite Difference Method

FDM is widely used in geotechnical engineering as it also can simulate the soil-structure interaction. In 1997, (Wong et al. 1997) simulated a nailed soil wall by FDM, and recently, Zheng et al. (2017) and Zhu & Huang (2017) analysed damage to embankments by this method. Zhang et al. (2017) also carried out an interesting study on the damage found in an operational tunnel. Although FDM is not widely used in structural engineering, as can be seen from the works cited above, it is a valuable tool for solving geotechnical problems.

5. CONCLUSIONS

Computerised numerical simulation is very useful for assessing structures or determining the causes of a failure. The JPCF is a reference in the field of structural failures. Numerical simulation has now become a habitual method of studying structural behaviour and its use is steadily growing. The most widely used technique for this is, by far, FEM, although excellent results can also be obtained by AEM and FDM in areas such as progressive collapse, blast loading, and soil-structure interaction, among others.

These techniques, which include nonlinear modelling, are particularly valuable in failure analysis and forensic engineering. For design, relatively simple linear analysis is satisfactory, since engineers and architects are simply trying to ensure safe behaviour up until failure of the first critical component. However, in failure analysis, it may become important to explain what happened after that first component failed, what failed next, and why the broken pieces ended up where they did.

This paper has described the experience of the Editors and Associated Editors of the JPCF in relation to the use of numerical simulation for assessing structures and analysing failures. A very brief description has been given of the journal's special number published in 2013 on actual failures as analysed by numerical models. Also described are the three most widely used simulation techniques in the papers published by the journal, together with some representative examples of each one.

REFERENCES

Altunişik A.C., Ateş Ş., Hüsem M.: Effect of construction errors on the snow-induced failure of a Tribune's columns and roof. *Journal of Performance of Constructed Facilities*, 31(3), 2017

Augenti N., Parisi F.: Buckling analysis of a long-span roof structure collapsed during construction. *Journal of Performance of Constructed Facilities*, 27(1), 2013.

Bartoli G., Betti M.: Cappella dei Principi in Firenze, Italy: Experimental analyses and numerical modeling for the investigation of a local failure. *Journal of Performance of Constructed Facilities*, 27(1), 2013.

Bartoli G., Betti M., Blasi C., Ottoni F., Coli M., Marchetti E., Ripepe, M.: Synergistic and Interdisciplinary Approaches for the Conservation of Monumental Heritage: Cupola of Santa Maria del Fiore in Florence, Italy. *Journal of Performance of Constructed Facilities*, 30(4), 2016.

Çavdar Ö., Bayraktar A.: Nonlinear Earthquake Performance Evaluation of a Structure Collapsed during the Van, Turkey, Earthquake on October 23, 2011. *Journal of Performance of Constructed Facilities*, 30(4), 2016.

Chehab A.I., Eamon C.D., Griffin J.: Collapse Resistance of RC Moment-Resisting Frame and Shear Wall Structural Systems Exposed to Blast. *Journal of Performance of Constructed Facilities*, 31(2), 2017.

Chen S.-L., Lee S.-C., Wei Y.-S.: Numerical Analysis of Ground Surface Settlement Induced by Double-O Tube Shield Tunneling. *Journal of Performance of Constructed Facilities*, 30(5), 2016.

Gu X.-L., Yu Q.-Q., Li Y., Lin F.: Collapse Process Analysis of Reinforced Concrete Super-Large Cooling Towers Induced by Failure of Columns. *Journal of Performance of Constructed Facilities*, 31(5), 2017.

Hejazi M., Moayedian S.M., Daei M.: Structural Analysis of Persian Historical Brick Masonry Minarets. *Journal of Performance of Constructed Facilities*, 30(2), 2016.

Helmy H., Salem H., Mourad S.: Computer-aided assessment of progressive collapse of reinforced concrete structures according to GSA code. *Journal of Performance of Constructed Facilities*, 27(5), 2013.

Khalil A.A.: Enhanced modeling of steel structures for progressive collapse analysis using the applied element method. *Journal of Performance of Constructed Facilities*, 26(6), 2012.

Laurendeau M., Barr P. J., Higgs A., Halling M.W., Maguire M., Fausett R.W.: Live-Load Response of a 65-Year-Old Pratt Truss Bridge. *Journal of Performance of Constructed Facilities*, 29(6), 2015.

Li J., Guo L.: Field Investigation and Numerical Analysis of Residential Building Damaged by Expansive Soil Movement Caused by Tree Root Drying. *Journal of Performance of Constructed Facilities*, 31(1), 2017.

Lindquist W., Ibrahim A., Tung Y., Motaleb M., Tobia, D., Hindi R.: Distortion-Induced Fatigue Cracking in a Seismically Retrofitted Steel Bridge. *Journal of Performance of Constructed Facilities*, 30(4), 2016.

Liu J., Song J., Zhang Z., Hu N.: Influence of the Ground Displacement and Deformation of Soil around a Tunnel Caused by Shield Backfilled Grouting during Construction. *Journal of Performance of Constructed Facilities*, 31(3), 2017.

Lourenço P.B., Medeiros P.: Learning from failure of a long curved veneer wall: Structural analysis and repair. *Journal of Performance of Constructed Facilities*, 27(1), 2013.

Mortezaei A., Motaghi, A.: Seismic Assessment of the World's Tallest Pure-Brick Tower Including Soil-Structure Interaction. *Journal of Performance of Constructed Facilities*, 30(5), 2016.

Rajagopal S., Kang T.H.-K.: Distress Evaluation and Rehabilitation of Damaged RC-Framed Coal-Storage-Yard Structure in Thermal Power Plant. *Journal of Performance of Constructed Facilities*, 30(2), 2016.

Salem H., Mohssen S., Nishikiori Y., Hosoda A.: Numerical Collapse Analysis of Tsuyagawa Bridge

Damaged by Tohoku Tsunami. *Journal of Performance of Constructed Facilities*, 30(6), 2016.

Seo J., Hosteng T.K., Phares B.M., Wacker J.P.: Live-Load Performance Evaluation of Historic Covered Timber Bridges in the United States. *Journal of Performance of Constructed Facilities*, 30(4), 2016.

Vercher J., Gil E., Mas A., Lerma C.: Diagnosis and Intervention Criteria in Slabs Damaged by Severe Corrosion of Prestressed Joists. *Journal of Performance of Constructed Facilities*, 29(1), 2015.

Wilcoski J., Heymsfield E.: Performance and Rehabilitation of Type L FAA Airport Traffic Control Tower at San Carlos, California, for Seismic Loading. *Journal of Performance of Constructed Facilities*, 16(2), 85–93, 2002.

Wong I.H., Low B.K., Pang P. Y., Raju G.V.R.: Field performance of nailed soil wall in residual soil. *Journal of Performance of Constructed Facilities*, 11(3), 1997.

Yekrangnia M., Mobarake, A.A.: Restoration of historical Al-Askari shrine. II: Vulnerability assessment by numerical simulation. *Journal of Performance of Constructed Facilities*, 30(3), 2016.

Zhang Y., Shi Y., Zhao Y., Yang J.: Damage in Concrete Lining of an Operational Tunnel. *Journal of Performance of Constructed Facilities*, 31(4), 2017.

Zheng Y., Hatami K., Miller G.A.: Numerical simulation of wetting-induced settlement of embankments. *Journal of Performance of Constructed Facilities*, 31(3), 2017.

Zhu C.Q., Huang, Y.: Safety Assessment of Antiliquefaction Performance of a Constructed Reservoir Embankment. II: Numerical Assessment. *Journal of Performance of Constructed Facilities*, 31(2), 2017.