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50 YEARS

INSTITUTE OF STRUCTURAL ENGINEERING,
EARTHQUAKE ENGINEERING
AND CONSTRUCTION IT

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Matej Fischinger

PREFACE

In 2021, a distinctive institute celebrated its 50th anniversary, namely the Institute of Structural Engineering, Earthquake Engineering and Construction IT (IKPIR), which reflects the essence of its foundation and success. There are thousands of structural engineering institutes worldwide and numerous earthquake engineering institutions, but IKPIR also incorporates computer science and information technology, making it unique. This preface is followed by a presentation of selected works we have created at IKPIR that illustrate long-lasting engagement and collaboration in all three areas of our activities. Each activity area is presented in a thematically devoted section.

The origins of IKPIR date back to 1971. It was originally established under a different name, the Computer Centre of Faculty of Architecture, Civil and Geodetic Engineering (FAGG), "by a group of a few young men, whose engineering and mathematical education was solid enough to at least keep up with worldwide developments in this field (i.e., the use of computers in civil engineering)", as the distinguished structural engineer and professor Svetko Lapajne called them. It was not just a matter of education but, more importantly, a vision and youthful enthusiasm that soon transformed the followers into creators and, in some fields, leaders of worldwide development. The name Computer Centre of FAGG, which many considered only as a support service for introducing computer skills to faculty Chairs, did not reflect the true potential of this group. Its potential was rooted primarily in developing the necessary knowledge, calculation methods and software for civil engineers, by civil engineers, with the support of IT professionals and mathematicians. This gave the Institute a significant comparative advantage over similar institutions in the world, many of which often used software developed elsewhere. For these other institutions, the link between the understanding of the structure and the software as well as the implementation of the structural models in

practice, has been less widespread. On the other hand, the software developed at IKPIR was extremely practical and quickly found its way into designing civil engineering structures. There are not many institutions in the world that can tout a similar record over the past several decades, boasting that the most important buildings throughout the country were designed using the software they developed.

An essential feature of the Institute's activities in the early decades was the extraordinary mutual respect between the young men working at the IKPIR and the leading structural engineers of that period. I, for one, fondly remember entering the offices of engineers (at first as a student) and meeting Adamič and Sterlekar, Prof. Prelog and other authorities in the field of structural design. They returned the respect by acknowledging the contribution of young men and guiding them with advice on modelling and engineering insight. I believe that the collaboration between the developers of computational methods and software developers, as well as the designers, specialists for structural design and IT specialists, led to the Institute's extraordinary research successes. Particularly, high-profile results were achieved in the new scientific discipline of earthquake engineering in Slovenia, led by Peter Fajfar. At the time, the Institute was not able to compete with large global institutions in terms of staff numbers, development resources or equipment. Nevertheless, Peter Fajfar, Janez Duhovnik, Janez Reflak, Ervin Prelog, Iztok Kovačič, Zdene Breška and later Frano Damjanić, as well as numerous others who followed them, understood how to combine the most modern trends in science with engineering models, methods and structural software. A little later, Žiga Turk and his colleagues, as civil engineers, could see the potential and the ever-changing challenges in information technology, involving a broader perspective than their colleagues around the world. Particularly, the following collection of selected works illustrates how the above-mentioned comparative advantages have raised the Institute alongside other prominent and famous research institutions in the world's most developed countries.

With rapid and successful breakthroughs in both the professional and academic fields, the Computer Centre of FAGG greatly exceeded the scope of its name. At the end of 1979, it was renamed the Institute of Structural Engineering, Earthquake Engineering and Construction IT,

which better reflected the research, teaching and professional nature, and outlined three interwoven areas of work. In the years that followed, IKPIR emerged as the faculty's strongest teaching and internal research division.

The Institute had another major advantage, significantly shaped by the successful leadership of Janez Reflak, who developed an exceptional working atmosphere and cooperation among all team members. This mindset could be described as a fusion of Japanese institutional discipline and individual creativity in Western cultures. Due to the various personalities, good relationships were developed based on a synthesis of necessary hierarchal and individual initiatives, where there was no room for narrow or selfish goals. After Reflak's retirement in 2001, the successful management was continued until 2012 by Peter Fajfar, who had also headed the Institute between 1985 and 1989. Then, I took over the head post and, in 2020, handed it over to the caring hands of the current head, Tatjana Isaković.

In today's world of accelerating changes, however, it is not the biggest and most successful who remain, but the most adaptable. The somewhat romantic scheme of the Institute's activities in the early decades, which I remember with nostalgia, became too narrow for its further development at the beginning of the millennium. It became clear that with the rapid development of research and the profession, a single person cannot competently manage all three areas of the Institute's activities. It also became clear that the academic institution was not primarily intended to maintain the software in a rapidly changing IT environment. The formalisation of these new relations took place in early 2001 when two Chairs were established within IKPIR: the Chair of Structural and Earthquake Engineering (KKPI) and the Chair of Construction IT (KGI). The two Chairs continue to collaborate in research and teaching. A typical area of cooperation and connection between the Chairs is the field of numerical modelling, which enables virtual simulations of the behaviour of materials and structures in engineering applications. For this purpose, a powerful computing environment and structured information are needed. The leading person in this work is Boštjan Brank, a member of KKPI, who conducts the research with his colleagues within the research group of KGI. Notably, many modern approaches to teaching have been introduced due to the cooperation in the teaching field as

part of the Interdisciplinary Seminar on Computer-Aided Design of Structures.

While the new organisational structure has necessarily undermined the characteristic homogeneity of the original Institute, it has, on the other hand, led to an extraordinary and very successful development of relevant scientific fields and an even stronger establishment of the Institute's staff in the international environment. Several of the greatest successes and works are presented below. A superficial look at the selected abstracts might give the impression that they are mainly the result of individual groups. All these groups, however, are built on solid foundations laid by young pioneers at the time of the Institute's founding - visionary knowledge and enthusiasm for new technologies, orientation toward engineering approaches to problem-solving, scientific excellence, and openness to the world.

To conclude, we take the liberty of listing the achievements of the Institute's colleagues, which has achieved world-class results despite its relatively small size. Among the Institute's staff and students, there has been a myriad of notable recognitions, including a member of several academies of science in the world, who was also the first Slovenian to be elected as a foreign member of the National Academy of Engineering in the USA, and recipients of national awards for scientific work and awards from the Chamber of Engineers of Slovenia, editors of world-leading scientific journals, leaders and partners of numerous research projects in Europe and the world, exceptionally cited authors, reviewers of the most demanding professional national and international projects, outstanding professors the first full-time woman professor at FGG, dean of FAGG and FGG (Faculty of Civil and Geodetic Engineering), four ministers of the government of the Republic of Slovenia, president of the Slovenian Chamber of Engineers, CEO of the Slovenian Motorway Company DARS, as well as leading designers and directors of major construction companies. Some colleagues are also successful in professions not directly related to research and structural engineering, which reflects the diversity and breadth of spirit that has always been present at IKPIR. All the young visionaries, as well as the second-year students who joined them in 1974, including myself, are retired. Younger colleagues, who have already helped shape the development of IKPIR, will embark on new paths of development based on the solid foundation and network described above.

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FAJFAR Peter

Numerična analiza večetažnih objektov/ Numerical analysis of multistorey buildings

Gradbeni vestnik, 1974, Vol. 23(8/9): 212-220

ABSTRACT

Original abstract in Slovene language: Pokazani so osnovni principi splošne metode za statično, dinamično in stabilnostno analizo večetažnih objektov . Metoda omogoča enostaven in ekonomičen račun vseh običajnih konstrukcij v visokogradnji. Možno je upoštevati poljubno tlorisno razporeditev poljubnih nosilnih elementov, spreminjanje statičnih in dinamičnih karakteristik po višini objekta, različno višino konstrukcije po posameznih delih tlorisa in elastično vpetost. Predpostavljeno je elastično obnašanje materiala in veljavnost teorije drugega reda (majhni premiki). Medetažne plošče so neskončno toge v svoji ravnini in neskončno gibke normalno na to ravnino. Eksplicitno so upoštevane samo tiste bistvene prostostne stopnje, ki imajo največji vpliv na obnašanje konstrukcije, to so premiki v horizontalnih ravninah.

English translation: The basic principles of a general method for static, dynamic and stability analysis of non-symmetrical multi-storey structures are presented. The method enables simple and economical structural analysis of all common buildings. It is possible to take into account any ground-plan arrangement of different macroelements (substructures such as frames, walls, coupled walls and walls on columns), different heights of stories, the changing of static and dynamic characteristics along the height of a building, the macroelements of different heights, and the elastic foundation. The elastic behaviour of material and the validity of the 2nd order theory (small displacements) are assumed. The floor slabs are rigid in their own planes and have no out-of-plan flexural stiffness. Only the essential degrees of freedom that have the largest influence on the behaviour of the structure, i.e., the translations and rotations in the horizontal planes, are explicitly taken into account.

FAJFAR Peter, FISCHINGER Matej

Non-linear seismic analysis of RC buildings : implications of a case study

European earthquake engineering, 1987, Vol. 1(1): 31-43

ABSTRACT

The non-linear seismic response of a 7-story RC frame-wall building has been studied analytically and compared with the experimental results obtained within the framework of the joint U.S. - Japan research project in Tsukuba. Based on the results of the study of investigated building, some generally applicable conclusions on analysis procedures for RC buildings subjected to strong earthquakes have been drawn. Two methods of analvsis have been applied: a) the nonlinear dynamic analysis of a multi-degree-of-freedom (MDOF) system performed by an extended version of the DRAIN-2D program; b) a simplified non-linear procedure (N2) including the non-linear static analysis of the same MDOF system and the non-linear dynamic analysis of an equivalent single-degree-of-freedom (SDOF) system. The dynamic analysis of the SDOF system can be additionally simplified by using inelastic response spectra. It is shown that both methods can yield realistic results for the general structural behaviour provided the characteristics of the earthquake loading are known and the most important experimental findings are included in the mathematical model. In design, however, where the future ground motion is uncertain, and where experimental results are not available, the N2 method is recommended (at least for "regular" buildings oscillating predominantly in a single mode), due to its relative simplicity. It is preferred also to the common design procedures based on either the elastic equivalent lateral force procedure or elastic spectral modal analysis, which are unable to estimate properly the two of the most important structural parameters: strength and ductility.

FAJFAR Peter, FISCHINGER Matej

N2-a method for non-linear seismic analysis of regular buildings

Proceedings 9th World Conference on Earthquake Engineering, August 2-9, 1988, Tokyo-Kyoto, Japan. pp 111-116

ABSTRACT

The basic ideas of a relatively simple method for the non-linear seismic analysis of reasonably regular buildings oscillating predominantly in a single mode are presented. The method was applied to the analysis of the 7-story RC frame-wall building tested in Tsukuba within the joint U.S. – Japan project. The results were compared with the test results and with the analytical results obtained by the non-linear analysis of a MDOF mathematical model, using DRAIN-2D. A fair correlation of the global structural response was observed.

FISCHINGER Matej, FAJFAR Peter

On the response modification factors for reinforced concrete buildings

Proceedings of 4th U.S. National conference on earthquake engineering, Palm Springs, California, May 20-24, 1990, pp. 249-258

ABSTRACT

Three different structural systems (ductile frame, frame-wall, and bearing shear-wall) were chose for a 10-storey RC building, and each of them was designed for two different levels of the design seismic forces (response modification factors R). The general level of the R-factors which are currently used in some typical U.S. codes proved to be adequate, due to the considerable overstrength in the analysed buildings. In order to take into account this overstrength properly, it is proposed that R-factors are defined as the product of the equivalent global ductility factor Rμ and the overstrenth factor Rs and/or that simplified inelastic analysis is gradually introduced into design procedures. Some comparisons of the R-factors as defined for different structural systems in different codes are included.

FAJFAR Peter

Equivalent ductility factors, taking into account low-cycle fatigue

Earthquake engineering & structural dynamics, 1992, Vol. 21(10): 837-848

ABSTRACT

During strong earthquakes, the deformation capacity of structures is reduced due to the cumulative damage caused by cyclic load reversals. In the paper, equivalent (reduced) ductility factors have been proposed, which take into account this effect. They are based on different failure hypotheses. Ductility reduction due to low-cycle fatigue is controlled by a dimensionless parameter γ, which is a function of dissipated hysteretic energy, maximum displacement and the natural frequency of the structural system, and which has been proved to be a relatively stable quantity in the whole period range. If approximate values for γ are used, the determination of equivalent ductility is very simple, and thus appropriate for design purposes. The formulae for equivalent ductility factors include damage indices, and permit the designer to choose acceptable level of structural damage explicitly. As an example, equivalent ductility factors have been used to construct inelastic acceleration spectra, which are proportional to strength demand for the El Centro 1940 S00E record. The results have been compared with the 'exact' spectra obtained by non-linear dynamic analysis.

VIDIC Tomaž, FAJFAR Peter, FISCHINGER Matej

Consistent inelastic design spectra : strength and displacement

Earthquake engineering & structural dynamics, 1994, Vol. 23(5):507-521

ABSTRACT

A procedure for the determination of inelastic design spectra (for strength, displacement, hysteretic and input energy) for systems with a prescribed ductility factor has been developed. All the spectra are consistent (interrelated and based on the same assumptions). This is the first of two companion papers which deals with the 'classical' structural parameters: strength and displacement. The input data are the characteristics of the expected ground motion in terms of a smooth elastic pseudo-acceleration spectrum. Simple, approximate expressions for the strength reduction factor R are proposed. The value of R depends on the natural period of the system, the prescribed ductility factor, the hysteretic behaviour, damping and ground motion. Fairly accurate approximations to the inelastic spectra for strength and displacement can be derived from the elastic spectrum using the proposed values for R.

FAJFAR Peter, VIDIC Tomaž

Consistent inelastic design spectra : hysteretic and input energy

Earthquake engineering & structural dynamics, 1994, Vol. 23(5): 523-537

ABSTRACT

A procedure for the determination of inelastic design spectra (for strength, displacement, hysteretic and input energy) for systems with a prescribed ductility factor has been developed. All the spectra are consistent (interrelated and based on the same assumptions). This is the first of two companion papers which deals with the 'classical' structural parameters: strength and displacement. The input data are the characteristics of the expected ground motion in terms of a smooth elastic pseudo-acceleration spectrum. Simple, approximate expressions for the strength reduction factor R are proposed. The value of R depends on the natural period of the system, the prescribed ductility factor, the hysteretic behaviour, damping and ground motion. Fairly accurate approximations to the inelastic spectra for strength and displacement can be derived from the elastic spectrum using the proposed values for R.

FAJFAR Peter, GAŠPERŠIČ Peter

The N2 method for the seismic damage analysis of RC buildings

Earthquake engineering & structural dynamics, 1996, Vol. 25(1): 31-46

ABSTRACT

A comprehensive, though relatively simple, non-linear method for the seismic damage analysis of reinforced concrete buildings (the N2 method) has been elaborated. The basic features of the method are: the use of two separate mathematical models, application of the response spectrum approach and of the non-linear static analysis, and the choice of a damage model which includes cumulative damage. The method yields results of reasonable accuracy provided that the structure oscillates predominantly in the first mode. Three variants of a seven-storey building have been used as illustrative examples for the application of the method. Four different types of the analysis, with different degrees of sophistication, have been performed in order to estimate the influence of several assumptions and approximations used in the N2 method.

KILAR Vojko, FAJFAR Peter

Simple push-over analysis of asymmetric buildings

Earthquake engineering & structural dynamics, 1997, Vol. 26(2):233-249

ABSTRACT

A simple method for the non-linear static analysis of complex building structures subjected to monotonically increasing horizontal loading (push-over analysis) is presented. The method is designed to be a part of new methodologies for the seismic design and evaluation of structures. It is based on the extension of a pseudo-three-dimensional mathematical model of a building structure into the non-linear range. The structure consists of planar macroelements. For each planar macroelement, a simple bilinear or multilinear base shear - top displacement relationship is assumed. By a step-by-step analysis an approximate relationship between the global base shear and top displacement is computed. During the analysis the development of plastic hinges throughout the building can be monitored. The method has been implemented into a prototype computer program. In the paper the mathematical model, the base shear - top displacement relationships for different types of macroelements, and the step-by-step computational procedure are described. The method has been applied for the analysis of a symmetric and an asymmetric variant of a seven-storey reinforced concrete frame - wall building, as well as for the analysis of a complex asymmetric 21-storey reinforced concrete wall building. The influence of torsion on structural behaviour is discussed.

FISCHINGER Matej, CEROVŠEK Tomo, TURK Žiga

Earthquake engineering slides on the Internet and CD-ROM

Proceedings of the 11th European conference on earthquake engineering, 1998, Paris, France, pp. 1-6

ABSTRACT

Hypermedia tool based on digital slides to learn from post-earthquake invistigations has been developed. The core of the tool consists of 500 digital images showing earthquake damage after four major earthquakes (Montenegro, 1979; Mexico City, 1985; Northridge, 1994; and Kobe, 1995). All slides are commented in detail, classified and labelled with keywords. Additionally, typical damage and background information is elaborated on. The system offers stat-of-the-art navigation, browse and search options using a combination of database technology and friendly Web hypertext interface. The system is available on the Web and on CD-ROM. Sample session with EASY demonstrates typical usage, capabilities, and educational potential of the system.

FAJFAR Peter

Capacity spectrum method based on inelastic demand spectra

Earthquake engineering & structural dynamics, 1999, Vol. 28(9): 979-993

ABSTRACT

By means of a graphical procedure, the capacity spectrum method compares the capacity of a structure with the demands of earthquake ground motion on it. In the present version of the method, highly damped elastic spectra have been used to determine seismic demand. A more straightforward approach for the determination of seismic demand is based on the use of the inelastic strength and displacement spectra which can be obtained directly by time-history analyses of inelastic SDOF systems, or indirectly from elastic spectra. The advantages of the two approaches (i.e. the visual representation of the capacity spectrum method and the superior physical basis of inelastic demand spectra) can be combined. In this paper, the idea of using inelastic demand spectra within the capacity spectrum method has been elaborated and is presented in an easy to use format. The approach represents the so-called N2 method formulated in the format of the capacity spectrum method. By reversing the procedure, a direct displacement-based design can be performed. The application of the modified capacity spectrum method is illustrated by means of two examples.

FAJFAR Peter

A nonlinear analysis method for performance-based seismic design

Earthquake spectra, 2000, Vol. 16(3): 573-592

ABSTRACT

A relatively simple nonlinear method for the seismic analysis of structures (the N2 method) is presented. It combines the pushover analysis of a multi-degree-of-freedom (MDOF) model with the response spectrum analysis of an equivalent single-degree-of-freedom (SDOF) system. The method is formulated in the acceleration - displacement format, which enables the visual interpretation of the procedure and of the relations between the basic quantities controlling the seismic response. Inelastic spectra, rather than elastic spectra with equivalent damping and period, are applied. This feature represents the major difference with respect to the capacity spectrum method. Moreover, demand quantities can be obtained without iteration. Generally, the results of the N2 method are reasonably accurate, provided that the structure oscillates predominantly in the first mode. Some additional limitations apply. In the paper, the method is described and discussed, and its basic derivations are given. The similarities and differences between the proposed method and the FEMA 273 and ATC 40 nonlinear static analysis procedures are discussed. Application of the method is illustrated by means of an example.

DOLŠEK Matjaž, FAJFAR Peter

Soft storey effects in uniformly infilled reinforced concrete frames

Journal of earthquake engineering, 2001, Vol. 5(1): 1-12

ABSTRACT

A large number of multi-storey reinforced concrete frame buildings with masonry infill walls, which were uniformly distributed over the height of the building, collapsed in the 1999 Kocaeli (Turkey) earthquake, due to complete failure of the first storey or the bottom two stories. In the paper it is demonstrated that a soft storey mechanism is formed in such structural systems if the intensity of ground motion is above a certain level, It is likely that collapse will occur if the global ductilities of the bare frames, as well as the ductilities of the structural elements, are low, and if the infill walls are relatively weak and brittle.

DOLŠEK Matjaž, FAJFAR Peter

IN2 - a simple alternative for IDA

Paper No. 3353. Proceedings of 13th World Conference on Earthquake Engineering, Vancouver, Canada, 1-6 August, 2004, pp. [1-15]

ABSTRACT

Simplified inelastic procedures used in seismic design and assessment combine the nonlinear static (pushover) analysis and the response spectrum approach. One of such procedures is the N2 method, which has been implemented into the Eurocode 8 standard. The N2 method can be employed also as a simple tool for the determination of the approximate summarized IDA (incremental dynamic analysis) curve. Such analysis is called the incremental N2 method (IN2). The IN2 curve can substitute the IDA curve in the probabilistic framework for seismic design and assessment of structures. In the paper, the IN2 method is summarized and applied to two test examples of infilled reinforced concrete (RC) frames, which are characterized by a substantial degradation of the strength after the infill fails. The approximate summarized IDA curves, determined by the IN2 method, and the data on dispersion due to randomness in displacement demand, determined in a previous study by the authors, were employed in the probabilistic risk analysis of test structures. The results were compared with the results obtained using the “exact” IDA curves. A fair correlation of results suggests that the IN2 method is a viable approach.

FAJFAR Peter, MARUŠIĆ Damjan, PERUŠ iztok

Torsional effects in the pushover-based seismic analysis of buildings

Journal of earthquake engineering, 2005, Vol. 9(6):831-854

ABSTRACT

The general trends of the inelastic behaviour of plan-asymmetric structures have been studied. Systems with structural elements in both orthogonal directions and bi-axial eccentricity were subjected to bi-directional excitation. Test examples include idealized single-storey and multi-storey models, and a three-storey building, for which test results are available. The response in terms of displacements was determined by nonlinear dynamic analyses. The main findings, limited to fairly regular and simple investigated buildings, are: (a) The amplification' of displacements determined by elastic dynamic analysis can be used as a rough, and in the majority of cases conservative estimate in the inelastic range. (b) Any favourable torsional effect on the stiff side, which may arise from elastic analysis, may disappear in the inelastic range. These findings can be utilised in the approximate pushover-based seismic analysis of asymmetric buildings, e.g. in the N2 method. It is proposed that the results obtained by pushover analysis of a 3D structural model be combined with the results of a linear dynamic (spectral) analysis. The former results control the target displacements and the distribution of deformations along the height of the building, whereas the latter results define the torsional amplifications. The proposed approach is partly illustrated and evaluated by test examples.

DOLŠEK Matjaž, FAJFAR Peter

Simplified non-linear seismic analysis of infilled reinforced concrete frames

Earthquake engineering and structural dynamics, 2005, Vol. 34(1): 49-66

ABSTRACT

The N2 method for simplified non-linear seismic analysis has been extended in order to make it applicable to infilled reinforced concrete frames. Compared to the simple basic variant of the N2 method, two important differences apply. A multi-linear idealization of the pushover curve, which takes into account the strength degradation which occurs after the infill fails, has to be made, and specific reduction factors, developed in a companion paper, have to be used for the determination of inelastic spectra. It is shown that the N2 method can also be used for the determination of approximate summarized IDA curves. The proposed method was applied to two test buildings. The results were compared with the results obtained by non-linear dynamic analyses for three sets of ground motions, and a reasonable accuracy was demonstrated. A similar extension of the N2 method can be made to any structural system, provided that an appropriate specific R–μ–T relation is available.

PERUŠ Iztok, POLJANŠEK Karmen, FAJFAR Peter

Flexural deformation capacity of rectangular RC columns determined by the CAE method

Earthquake engineering & structural dynamics, 2006, Vol. 35(12): 1453-1470

ABSTRACT

A non-parametric empirical approach, called the conditional average estimator (CAE) method, has been implemented for the estimation of the flexural deformation capacity of reinforced concrete rectangular columns expressed in terms of the ultimate ('near collapse') drift. Two databases (PEER and Fardis), which represent subsets of the original databases, were used. Four input parameters were employed in the basic model: axial load index, index related to confinement, shear span index, and concrete compressive strength. The results of analyses suggest that, in general, ultimate drift decreases with increasing axial load index, and increases with better confinement. An increase in the shear span-to-depth ratio has a beneficial effect until a turning point is reached. After that the opposite trend can be observed, i.e. a decrease in the ultimate drift with further increasing of the shear span-to-depth ratio. No clear trend is observed in the case of concrete compressive strength. The predictions, obtained by using the Fardis database are in general somewhat larger than the predictions from the PEER database, due to the difference in the definition of ultimate drift. The scatter of results is large. The local coefficient of variation, which is a measure for dispersion, amounts to about 0.2–0.5. The ultimate drifts obtained by using the two databases, were compared with the values predicted by the Eurocode 8 empirical formula.

ISAKOVIĆ Tatjana, FISCHINGER Matej

Higher modes in simplified inelastic seismic analysis of single column bent viaducts

Earthquake engineering & structural dynamics, 2006, Vol. 35(1): 95-114

ABSTRACT

The influence of the higher modes and their consideration in the pushover analysis of reinforced concrete single column bent viaducts with different degree of irregularity is discussed. Typical multimode pushover-based methods (modal pushover analysis, modal adaptive non-linear static procedure and incremental response spectrum analysis) are addressed and compared with a single mode procedure (N2) and inelastic time history analysis.

If in the transverse direction the substructure of the viaduct is flexible in comparison with the superstructure, the influence of higher modes is small (the structure is regular) and single mode procedure works well. This typically occurs when the columns are high or considerably damaged. Conversely, for the analysis of irregular structures having short and slightly damaged columns, the multimode methods are needed. In most cases, all the analysed multimode pushover-based methods have given the results comparable with time history analysis, with the exception of cases where torsional sensitivity is varying during the response. All the methods have limitations (discussed in detail in the paper), which should be fully recognized by the user.

DOLŠEK Matjaž, FAJFAR Peter

Simplified probabilistic seismic performance assessment of plan-asymmetric buildings

Earthquake engineering & structural dynamics, 2007, Vol. 36(13): 2021-2041

ABSTRACT

A relatively simple approach for the probabilistic seismic performance assessment of plan-asymmetric structures has been proposed. It is based on the PEER probabilistic framework, in which the most demanding part, i.e. the incremental dynamic analysis (IDA), is replaced by the much simpler Incremental N2 (IN2) analysis. Predetermined default values for dispersion measures are needed for the practical implementation of this approach, which can be used for the analysis of plan-asymmetric buildings requiring a 3D structural model. In this paper, this simplified approach is summarized. Its application is demonstrated by means of an example of a three-storey reinforced concrete frame (SPEAR) building. The results are compared with the results of a more accurate approach, based on IDA. The test example demonstrates the viability of the proposed approach.

FISCHINGER Matej, KRAMAR Miha, ISAKOVIĆ Tatjana

Cyclic response of slender RC columns typical of precast industrial buildings

Bulletin of earthquake engineering, 2008, Vol. 6(3): 519-534

ABSTRACT

The cyclic behaviour of slender cantilever columns in full-scalemodels of precast industrial buildings, designed by Eurocode 8, was studied experimentally and analytically. The shear span ratio of the columns was 12.5, which is more than allowed by Eurocode 8 for columns in frame structures (10). High deformability and a large deformation capacity (8% drift) of the columns was observed. A lumped plasticity model was used in the analysis. In the paper the observed behaviour of the models has been compared with the predicted behaviour obtained by several empirically based models and procedures. It was observed that these models, which were developed for much lower shear span ratios (2–6), were not applicable for the analyzed very slender columns without appropriate additional considerations and modifications. In the case of such columns the yield drift is dominated by the flexural mode (it is practically proportional to the height of the column) and the ultimate drift under cyclic loading conditions is only slightly dependent on the shear span (indicating that the ratio of the equivalent length of the plastic hinge to the height of the column decreases with the increasing shear span). An appropriately modified lumped plasticity model incorporating in-cycle and repeated-cycle strength deterioration was chosen for future use in performance-based design and seismic risk studies.

ISAKOVIĆ Tatjana, POPEYO LAZARO Mauro Nino, FISCHINGER Matej

Applicability of pushover methods for the seismic analysis of single-column bent viaducts

Earthquake engineering & structural dynamics, 2008, Vol. 37(8): 1185-1202

ABSTRACT

An overview of the applicability of a typical single-mode pushover method (the N2 method) and two typical multi-mode pushover methods (the modal pushover analysis (MPA) and incremental response spectrum analysis (IRSA) methods) for the analysis of single column bent viaducts in the transverse direction is presented. Previous research, which was limited to relatively short viaducts supported by few columns, has been extended to longer viaducts with more bents.

The single-mode N2 method is accurate enough for bridges where the effective modal mass of the fundamental mode is at least 80% of the total mass. The applicability of this method depends on (a) the ratio of the stiffness of the superstructure to that of the bents and (b) the strength of the bents. In short bridges with few columns, the accuracy of the N2 method increases as the seismic intensity increases, whereas in long viaducts (e.g. viaducts with lengths greater than 500 m) the method is in general less effective.

In the case of the analyzed moderately irregular long viaducts, which are common in construction design practice, the MPA method performed well. For the analysis of bridges where the modes change significantly, depending on the seismic intensity, the IRSA method is in principle more appropriate, unless a viaduct is torsionally sensitive. In such cases, all simplified methods should be used with care.

DOLŠEK Matjaž, FAJFAR Peter

The effects of masonry infills on the seismic response of a four-storey reinforced concrete frame - a deterministic assessment

Engineering structures, 2008, Vol. 30(7): 1991-2001

ABSTRACT

The effect of masonry infills on the seismic response of a four-storey reinforced concrete frame has been studied using the N2 method. The method is based on pushover analysis and the inelastic spectrum approach. It was recently extended in order to make it applicable to infilled reinforced concrete frames. In the paper the method is summarized and applied to the deterministic seismic assessment of a four-storey reinforced concrete frame with masonry infills, with openings and without them. A comparison has been made with the behaviour of the bare frame. The most common analytical modelling technique, which employs compressive diagonal struts for modelling of the masonry infill, and one-component lumped plasticity elements for modelling the flexural behaviour of the beams and columns, was applied. The results of the analyses indicate that the infills can completely change the distribution of damage throughout the structure. The infills can have a beneficial effect on the structural response, provided that they are placed regularly throughout the structure, and that they do not cause shear failures of columns.

DOLŠEK Matjaž

Incremental dynamic analysis with consideration of modeling uncertainites

Earthquake engineering & structural dynamics, 2009, Vol. 38(6): 805-825

ABSTRACT

Incremental dynamic analysis (IDA) has been extended by introducing a set of structural models in addition to the set of ground motion records which is employed in IDA analysis in order to capture record-to-record variability. The set of structural models reflects epistemic (modeling) uncertainties, and is determined by utilizing the latin hypercube sampling (LHS) method. The effects of both aleatory and epistemic uncertainty on seismic response parameters are therefore considered in extended IDA analysis. The proposed method has been applied to an example of the four-storey-reinforced concrete frame, for which pseudo-dynamic tests were performed at the ELSA Laboratory, Ispra. The influence of epistemic uncertainty on the seismic response parameters is presented in terms of summarized IDA curves and dispersion measures. The results of extended IDA analysis are compared with the results of IDA analysis, and the sensitivity of the seismic response parameters to the input random variable using the LHS method is discussed. It is shown that epistemic uncertainty does not have significant influence on the seismic response parameters in the range far from collapse, but could have a significant influence on collapse capacity.

ISAKOVIĆ Tatjana, ZEVNIK Jaka, FISCHINGER Matej

Floor response spectra in isolated structures subjected to earthquakes weaker than the design earthquake. Part 2, Isolation with magnetically controlled elastomeric bearings

Structural control & health monitoring, 2011, Vol. 18(5): 540-553

ABSTRACT

The stiffness of rubber bearings typically increases during weak earthquakes. This can reduce the efficiency of the isolation and jeopardize the equipment installed in structures isolated with such bearings. The problems and the parameters influencing the response of the equipment in structures isolated by high-damping rubber bearings (HDRB) have been systematically analyzed in the accompanying article. To improve the response of rubber isolators in the case of lower seismic intensities, a new isolation device, which adjusts itself to the intensity of the load, has been developed. It is made from a magnetically controlled elastomer (MCE), i.e. a rubber-like material whose stiffness can be varied by applying a magnetic field. The main topic of this research is the evaluation of the efficiency of this new device. In order to be able to test it, appropriate numerical models of the device and the control algorithm have been developed. The efficiency of the new MCE device for the protection of equipment subjected to weak earthquakes has been systematically studied using non-linear acceleration floor spectra. It was found that the majority of the parameters influencing the response in structures isolated by conventional HDRB also influence the effectiveness of the new device. Besides these parameters, the effectiveness of the new MCE was found to be heavily dependent on the stiffness of the superstructure and on the thresholds of the control algorithm of the device. The MCE is more effective in the protection of equipment installed in very stiff structures.

KRESLIN Maja, FAJFAR Peter

The extended N2 method considering higher mode effects in both plan and elevation

Bulletin of earthquake engineering, 2012, Vol. 10(2):695-715

ABSTRACT

The extended N2 method has been developed, which takes into account higher mode effects both in plan and in elevation. The extension is based on the assumption that the structure remains in the elastic range when vibrating in higher modes. The seismic demand in terms of displacements and storey drift can be obtained by combining the results of basic pushover analysis and those of standard elastic modal analysis. In the paper, the proposed procedure was summarized and applied to a test example which represents an actual 8-storey reinforced concrete building. The results obtained by the extended N2 method were compared with the results of nonlinear response history analysis and basic N2 analysis without the consideration of higher modes. The extended N2 method was able to provide fair, conservative estimates of response in the case of the test example. In comparison to the basic N2 method, the prediction of seismic demand was greatly improved in the upper part of the building and at the flexible edges.

REJEC Klemen, ISAKOVIĆ Tatjana, FISCHINGER Matej

Seismic shear force magnification in RC cantilever structural walls, designed according to Eurocode 8

Bulletin of earthquake engineering, 2012, Vol. 10(2): 567-586

ABSTRACT

The paper contains a discussion of the inelastic dynamic magnification of seismic shear forces in cantilever walls with rectangular cross-sections. An extensive parametric study was performed in order to determine the reliability of the procedure in Eurocode 8 (EC8). A large number of single cantilever walls which are characteristic for the design practice in Europe and designed to satisfy all the EC8 requirements were analysed. The results obtained with the (modified) code procedures were compared with the results of inelastic response history analyses. If properly applied, the EC8 procedure for DCH walls usually yields good results for the base shears. However, as presently formulated and understood in the EC8, it can yield significantly incorrect results (overestimations of up to 40%). For this reason three modifications were introduced: (1) Keintzel's formula, which is adopted in EC8, should be used in combination with the seismic shears obtained by considering the first mode of the excitation only; (2) the upper limit of the shear magnification factor should be related to the total shear force; and (3) a variable shear magnification factor along the height of the wall should be applied. The present procedure in EC8 for DCM structures (using a constant shear magnification factor of 1.5 for all walls) is non-conservative. For DCM walls it is strongly recommended that the same procedure as required for DCH walls be used.

CELAREC Danijel, RICCI Paolo, DOLŠEK Matjaž

The sensitivity of seismic response parameters to the uncertain modelling variables of masonry-infilled reinforced concrete frames

Engineering structures, 2012, Vol. 35: 165-177

ABSTRACT

The sensitivity of the seismic response parameters to the uncertain modelling variables of the infills and frame of four infilled reinforced concrete frames was investigated using a simplified nonlinear method for the seismic performance assessment of such buildings. This method involves pushover analysis of the structural model and inelastic spectra that are appropriate for infilled reinforced concrete frames. Structural response was simulated by using nonlinear structural models that employ one-component lumped plasticity elements for the beams and columns, and compressive diagonal struts to represent the masonry infills. The results indicated that uncertainty in the characteristics of the masonry infills has the greatest impact on the response parameters corresponding to the limit states of damage limitation and significant damage, whereas the structural response at the near-collapse limit state is most sensitive to the ultimate rotation of the columns or to the cracking strength of the masonry infills. Based on the adopted methodology for the seismic performance assessment of infilled reinforced concrete frames, it is also shown, that masonry infills with reduced strength may have a beneficial effect on the near-collapse capacity, expressed in terms of the peak ground acceleration.

ZOUBEK Blaž, FISCHINGER Matej, ISAKOVIĆ Tatjana

Estimation of the cyclic capacity of beam-to-column dowel connections in precast industrial buildings

Bulletin of earthquake engineering, 2015, Vol. 13(7): 2145-2168

ABSTRACT

The behaviour of precast systems depends on the performance of the specific connections between the precast elements. In European precast design practice, the most common type of connection between beams and columns is a dowel connection. Such connections are subject to the following types of potential failure mechanism: (a) local failure characterized by the simultaneous yielding of the dowel and crushing of the surrounding concrete, and (b) global failure, characterized by spalling of the concrete between the dowel and the edge of the column or the beam. In this paper both types of failure of dowel connections are studied, although somewhat more attention is paid to the less investigated global failure. The local failure mechanism has been relatively well investigated, and the results have been presented in several studies. Thus only some minor changes are proposed in connection with the prediction of the related strength. On the other hand, the majority of existing procedures for the estimation of global strength are over-conservative since they neglect the influence of stirrups, or else only take them into account implicitly. None of these methods explicitly take into account the fact that the global failure of the dowel connection is changed by the presence of stirrups from brittle to ductile. In the paper, a new procedure for the estimation of resistance against global failure is proposed. Taking into account an appropriate strut and tie model of the connections, the influence of stirrups on this resistance as well as on the type of the failure is taken into account explicitly. Comparisons that were performed between the analytically calculated strength and the experimental results obtained have clearly shown that both of the proposed procedures for the estimation of resistance against local and global failure agree very well with the experimental results.

ZOUBEK Blaž, FISCHINGER Matej, ISAKOVIĆ Tatjana

Cyclic response of hammer-head strap cladding-to-structure connections used in RC precast building

Engineering structures, 2016, Vol. 119: 135-148

ABSTRACT

During the recent earthquakes in the Emilia-Romagna region of Italy, the cladding-to-structure connections which were installed in industrial precast buildings did not perform as had been expected in their design. According to the findings of some field reconnaissance reports, in several precast buildings collapse of cladding panels occurred. This indicated the need for new research and improvements in the design and execution of such connections. In this study the cyclic response of a cladding-to-structure connections which is most commonly used in the current European design practice of precast buildings was experimentally and analytically investigated. Such connections consist of cold-formed or hot-rolled channels and hammer-head straps. They provide the out-of-plane restraint at the top corners of vertical or horizontal panels. Up until now no information has been available, in the existing literature, about the cyclic response of such connections in the plane of the cladding panels. The results of the performed experimental studies were used to develop reliable numerical models of typical connections, and to define appropriate procedures for the safe design of in-use connections.

LAZAR SINKOVIĆ Nuša, BROZOVIČ Marko, DOLŠEK Matjaž

Risk-based seismic design for collapse safety

Earthquake engineering & structural dynamics, 2016, Vol. 45(9): 1451-1471

ABSTRACT

Risk-based seismic design, as introduced in this paper, involves the use of different types of analysis in order to satisfy a risk-based performance objective with a reasonable utilization rate and sufficient reliability. Differentiation of the reliability of design can be achieved by defining different design algorithms depending on the importance of a structure. In general, the proposed design is iterative, where the adjustment of a structure during iterations is the most challenging task. Rather than using automated design algorithms, an attempt has been made to introduce three simple guidelines for adjusting reinforced concrete frames in order to increase their strength and deformation capacity. It is shown that an engineer can design a reinforced concrete frame in a few iterations, for example, by adjusting the structure on the basis of pushover analysis and checking the final design by means of nonlinear dynamic analysis. A possible variant of the risk-based design algorithm for the collapse safety of reinforced concrete frame buildings is proposed, and its application is demonstrated by means of an example of an eight-storey reinforced concrete building. Four iterations were required in order to achieve the risk-based performance objective with a reasonable utilization rate.

FISCHINGER Matej, KANTE Peter, ISAKOVIĆ Tatjana

Shake-table response of a coupled RC wall with thin T-shaped piers

Journal of structural engineering, 2017, Vol. 143(5): 04017004

ABSTRACT

A shake-table test of a 1:3 scale model of a thin, lightly reinforced concrete (RC), 5-story coupled wall, representing a typical apartment building with a high wall-to-floor area ratio, was performed. The wall consisted of two T-shaped piers, faced to each other by the webs, which were connected at each story level by the coupling beam and slab. The wall was subjected to a series of uniaxial and biaxial seismic excitations. Two different structural details providing different degrees of confinement were used at the free edges without boundary columns. The lightly confined free edges of the flanges (using hairpin transverse reinforcement) behaved satisfactorily in the case of moderate seismic demand. Due to the beam–slab interaction and the slab, which was considerably ticker than in typical buildings, the coupling beams were much stronger than expected, causing brittle shear failure of the overloaded wall piers under bidirectional excitation. The analyzed wall developed substantial strength and low ductility. The main observations of the experiment were confirmed by the results of postexperimental analytical studies performed using a three-dimensional (3D) multiple vertical-line element model, which has been incorporated into a well-known open-code program system.

VUKOBRATOVIĆ Vladimir, FAJFAR Peter

Code-oriented floor acceleration spectra for building structures

Bulletin of earthquake engineering, 2017, Vol. 15(7): 3013-3026

ABSTRACT

In the seismic design and assessment of acceleration-sensitive equipment installed in buildings, floor acceleration spectra, which are based on an uncoupled analysis of the structure and the equipment, are usually used. However, in order to obtain an ‘‘accurate’’ determination of floor spectra, a complex and quite demanding dynamic response-history analysis is needed. Recently a method for the direct generation of floor acceleration spectra from ground motion spectra, taking into account the dynamic properties of the structure, has been developed and validated. It is based on the theory of structural dynamics, in combination with empirically determined values for the amplification factors in the resonance region. The method can be used for both elastic and inelastic multi-degree-of-freedom structures and equipment modelled as an elastic or inelastic single-degree-of-freedom oscillator. In the case of inelastic primary structures, the method is coupled with the pushover-based N2 method. The variant of the method which is presented in this note is intended for practical applications, e.g. for implementation in guidelines and codes, and it represents a simplified version of the original method. In addition to some simplifications, the option of taking into account the inelastic response of the equipment was added. In the note, the method is summarized, and all the formulae needed for the calculation of floor acceleration spectra are provided. A description of all steps of the analysis, together with all the relevant numerical data, is presented in a test example.

ZOUBEK Blaž, FISCHINGER Matej, ISAKOVIĆ Tatjana

Seismic response of short restrainers used to protect cladding panels in RC precast buildings

Journal of vibration and control, 2018, Vol. 24(4): 645-658

ABSTRACT

In the presented study, a second-line back-up system for the seismic protection of cladding panels in RC precast buildings is first presented. The system consists of special anchoring elements and a rope restrainer. The latter is activated only in the case when the existing connections between the primary structure and the panel fail, resulting in the occurrence of relatively large impact forces in the restrainer and in the anchoring elements. In order to adequately design the constitutive parts of the system, a simple yet sufficiently accurate procedure for the estimation of the impact forces is needed. A relatively easy-to-use formula was therefore proposed for this purpose. Next, an extensive parametric study, using response history analysis (RHA), was performed and the influence of several parameters affecting the impact forces in the restrainers was studied. The results obtained in the study were used to evaluate the proposed analytical formula. Considering the simplicity of the proposed formula, its accuracy was good. It can therefore be applied to the design of short restrainers which could be used in reinforced concrete (RC) precast buildings for the protection of cladding panels against the effects of earthquakes.

FAJFAR Peter

Analysis in seismic provisions for buildings - past, present and future : the fifth prof. Nicholas Ambraseys lecture

Bulletin of earthquake engineering, 2018, Vol. 16(7): 2567-2608

ABSTRACT

The analysis of structures is a fundamental part of seismic design and assessment. It began more than a 100 years ago, when static analysis with lateral loads of about 10% of the weight of the structure was adopted in seismic regulations. For a long time seismic loads of this size remained in the majority of seismic codes worldwide. In the course of time, more advanced analysis procedures were implemented, taking into account the dynamics and nonlinear response of structures. In the future methods with explicit probabilistic considerations may be adopted as an option. In this paper, the development of seismic provisions as related to analysis is summarized, the present state is discussed, and possible further developments are envisaged.

ISAKOVIĆ Tatjana, FISCHINGER Matej

Assessment of a force-displacement based multiple-vertical-line element to simulate the non linear axial-shear-flexure interaction behaviour of reinforced concrete walls

Bulletin of earthquake engineering, 2019, Vol. 17: 6369-6389,

ABSTRACT

A comprehensive assessment of a new version of the macroscopic force–displacement based multiple-vertical-line element (SFI-MVLEM-FD), which can be used to simulate non-linear axial–shear–flexure interaction in RC walls, is presented. The element models the shear response taking into account all the basic physical mechanisms that transfer shear forces over cracks: (a) the dowel effect of vertical bars, (b) the axial resistance of horizontal/shear bars, and (c) the interlocking of aggregate particles in cracks. In order to provide a wide range of its use, and to enable the analysis of various types of buildings, the SFI-MVLEM-FD element was included in the local version of the OpenSees program system. The element was assessed with respect to already performed quasi-static cyclic experiments of various RC shear walls. In this paper, the results of numerical analyses of two representative rectangular walls, where the influence of shear on the overall response was of particularly significance, are presented and compared with those obtained in the experiments. In order to estimate the efficiency of the new element in more general cases, it was also assessed by means of a large-scale shake-table test of a typical non-planar lightly reinforced RC coupled wall. The test examples showed that the SFI-MVLEM-FD model can capture all the important mechanisms of the response, as well as being able to efficiently describe the axial–shear–flexure interaction in various types of RC walls: (a) rectangular and non-planar, (b) cantilever and coupled, and (c) subjected to different types of excitation, uni-axial or bi-axial. It was found that the model is capable of clearly identifying the three fundamental mechanisms, which contribute to shear resistance. This is one of the few models, which are able to describe the significant deterioration of the (shear) strength of RC walls that are near to collapse for different reasons: e.g. the buckling of their longitudinal bars, rupture of the horizontal reinforcement, and other significant degradation of different types of shear mechanism. This makes it suitable for the analysis of different types of RC walls, which are subjected to different levels of seismic excitations. It is even able to simulate the near collapse response influenced by very different collapse mechanisms.

BABIČ Anže, DOLŠEK Matjaž

A five-grade grading system for the evaluation and communication of short-term and long-term risk posed by natural hazards

Structural safety, 2019, Vol. 78(May): 48-62

ABSTRACT

A five-grade grading system is introduced by combining together the concepts of long-term and short-term risk tolerance. Grades AA or A are related to a long-term tolerable risk, whereas grades B and C are considered acceptable only for a shorter period, depending on the facility performance, and grade D corresponds to a short-term intolerable risk. In the first step of the grading process, the initial grade is determined by comparing the estimated risk to a set of risk boundaries, which define the ranges between grades AA-A, A-B and B-C. If the estimated risk is found to be long-term intolerable (grade B or C), the second step follows. This approach utilizes the criterion of cumulative risk, which makes it possible to introduce a reduction in grades B or/and C over time, and in the additional grade D, which is associated with intolerable cumulative risk. The use of the proposed grading system is demonstrated by means of an example of two precast reinforced concrete buildings exposed to seismic risk, where grade B is initially assigned to the facility with better performance, whereas the other facility is evaluated by grade C. It is shown that the reduction of the grades to the lowest grade D is scheduled for 11.9 years and 3.8 years, respectively, in the case of the building with the lower and the higher risk. Such information can be used for communicating risk to stakeholders, and as a basis for the enhancing of the disaster risk management of communities.

ŽIŽMOND Jure, DOLŠEK Matjaž

Formulation of risk-targeted seismic action for the force-based seismic design of structures

Earthquake engineering & structural dynamics, 2019, Vol. 48(12): 1406-1428

ABSTRACT

A risk-targeted design spectral acceleration and the corresponding seismic design action for the force-based design of structures is introduced by means of two formulations. The first one called direct formulation utilizes the seismic hazard function at the site of the structure. Because the seismic action defined in the codes is often associated with a designated return period, an indirect formulation is also introduced. It incorporates a risk-targeted safety factor that can be used to define a risk-targeted reduction factor. It is shown that the proposed formulations give analogical results and provide an insight into the concept of the reduction of seismic forces for the force-based seismic design of structures if the objective is defined by a target collapse risk. The introduced closed-form solution for the risk-targeted reduction factor can be used to investigate how the target collapse risk, the seismic hazard parameters, the randomness of the seismic action, and the conventional parameters (ie, the overstrength factor and the deformation and energy dissipation capacity) affect the seismic design forces in the case of force-based design. However, collaborative research is needed in order to develop appropriate models of these parameters. In the second part of the paper, the proposed formulations are demonstrated by estimating the risk-targeted seismic design action for a six-storey reinforced concrete building. By verifying the collapse risk of the designed structure, it is demonstrated that the risk-targeted seismic action, in conjunction with a conventional force-based design, provided structure with acceptable performance when measured in terms of collapse risk.

SNOJ Jure, DOLŠEK Matjaž

Pushover-based seismic risk assessment and loss estimation of masonry buildings

Earthquake engineering & structural dynamics, 2020, Vol. 49(6): 567-588

ABSTRACT

A pushover-based seismic risk assessment and loss estimation methodology for masonry buildings is introduced. It enables estimation of loss by various performance measures such as the probability of exceeding a designated economic loss, the expected annual loss, and the expected loss given a seismic intensity. The methodology enables the estimation of the economic loss directly from the results of structural analysis, which combines pushover analysis and incremental dynamic analysis of an equivalent SDOF model. The use of the methodology is demonstrated by means of two variants of a three-storey masonry building both of which have the same geometry, but they are built, respectively, from hollow clay masonry (model H) and solid brick masonry (model S). The probability of collapse given the selected design earthquake corresponding to a return period of 475 years was found to be negligible for model H, which indicates the proper behaviour of such a structure when designed according to the current building codes. However, the corresponding probability of collapse of model S was very high (46%). The expected total loss given the design earthquake was estimated to amount to 28 000 € and 290 000 €, respectively, for models H and S. The expected annual loss per 100 m2 of gross floor area was estimated to amount to 75 € and 191 €, respectively, for models H and S. For the presented examples, it was also observed that nonstructural elements contributed more than 50% of the total loss.

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CELANO Francesca, DOLŠEK Matjaž

Fatality risk estimation for industrialized urban areas considering multi-hazard domino effects triggered by earthquakes

Reliability engineering & systems safety, 2021, No. 107287, Vol. 206, pp. 1-17

ABSTRACT

The rapid expansion of the built environment has resulted in the coexistence of industrial facilities and urban centres. Following recent major earthquakes throughout the world, it has become clear that multi-hazard domino effects can significantly increase the risk of fatalities, environmental problems and losses. This complex phenomenon is not yet well understood. In this paper, the problem is treated by decomposing it into several subproblems which are described by simplified probabilistic models. These models are then coupled with the Monte Carlo method to estimate the annual probability of fatality for an individual who is continuously standing in a location of interest and to estimate fatality risk maps for an area of interest. Emphasis is placed on considering multi-hazard domino effects, which can be triggered within an industrial area due to the damage caused by earthquakes. Thus it is considered that fatalities can be caused: a) as a direct consequence of seismic damage to a unit b) as a direct physical and/or chemical consequence due to the loss of containment of hazardous material, and c) as a consequence of domino triggered by physical and chemical events such as fire, explosion, and toxic dispersion. The capabilities of the proposed methodology are demonstrated by calculating fatality risk maps for a hypothetical industrialized urban area. It is shown that disregarding multi-hazard domino effects in the estimation of fatality risk could lead to significant underestimation of the fatality risk in an industrialized urban area. Thus, it is necessary to account for multi-hazard domino effects. However, different teams of engineers can enhance the models for the probability of fatality due to various phenomena, which will improve the accuracy of the proposed methodology.

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BABIČ Anže, DOLŠEK Matjaž, ŽIŽMOND Jure

Simulating historical earthquakes in existing cities for fostering design of resilient and sustainable communities : the Ljubljana case

Sustainability, 2021, Vol. 13(14), 7624, pp. 1-21

ABSTRACT

The seismic exposure of urban areas today is much higher than centuries ago. The 2020 Zagreb earthquake demonstrated that European cities are vulnerable even to moderate earthquakes, a fact that has been known to earthquake-engineering experts for decades. However, alerting decision-makers to the seismic risk issue is very challenging, even when they are aware of historical earthquakes that caused natural catastrophes in the areas of their jurisdiction. To help solve the issue, we introduce a scenario-based risk assessment methodology and demonstrate the consequences of the 1895 Ljubljana earthquake on the existing building stock. We show that a 6.2 magnitude earthquake with an epicentre 5 km north of Ljubljana would cause many deaths and severe damage to the building stock, which would likely lead to direct economic losses higher than 15% of the GDP of the Republic of Slovenia. Such an event would be catastrophic not only for the community directly affected by the earthquake but for the entire country. We have disseminated this information over the course of a year together in addition to formulating a plan for enhancing the community seismic resilience in Slovenia. Hopefully, local decision-makers will act according to their jurisdiction in Slovenia and persuade decision-makers across Europe to update the built environment renovation policy at the European level.

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DUHOVNIK Janez, FAJFAR Peter

Račun konstrukcij z elektronskimi računalniki/ Computer supported structural analysis

Gradbeni vestnik, 1969, Vol. 18(12):252-260

ABSTRACT

Modern electronic computers make possible the usage of new methods of statical analysis of structures. Different structures which, until now, could have been calculated only by extensive numerical computations, or by great simplifications, which many times greatly influenced the results, can now be solved exactly, quickly and cheap.

There is a brief survey of programs from the field of structures with special emphasis on STRESS program shown in this article. The simple method for computation of plain frames with members with variable cross section area is suggested and the way for the usage of STRESS program for the computation of shear walls with openings and combinations of frames with shear walls is described. Both the elastic restraint on the foundation soil and the rigid one are taken into account. There are two examples calculated and the comparison with the results from literature is shown as well. At last we are dealing with the method the computation of natural frequencies and characteric- program for the for the electronic computer is prepared. The whole process of dynamic analysis of structure with elastic shapes of structures, on the basis of which the help of computer is represented in this case.

DUHOVNIK Janez

Ekspertni sistemi v gradbeništvu/ Use of the expert systems in civil engineering

Gradbeni vestnik, 1989, Vol. 38(9/10):256-261

ABSTRACT

Original abstract in Slovene language: V članku so opisane lastnosti ekspertnih sistemov in njihov pomen za gradbeništvo. Prikazano je stanje v svetu in pri nas na tem področju.

English translation: The properties of the expert systems and their importance for civil engineering are described. The state-of-the art in the world and Slovenia is presented.

DUHOVNIK Janez, LJUBIČ Ladislav, KNIFIC Tone, ŽLAJPAH Dejan

AR-CAD programski sistem za projektiranje armature

Gradbeni vestnik,1990, Vol. 39(12): 303-309

ABSTRACT

Original abstract in Slovene language: V članku je opisan programski sistem AR_CAD za projektiranje armature v betonskih konstrukcijah. Predstavljen je proces projektiranja armature in faze projektiranja v programskem sistemu AR_CAD. Opisanih je nekaj primerov uporabe programskega sistema. Predlagan je način uvajanja računalniškega projektiranja armature v delo projektantov.

English translation: The article describes the AR_CAD software system for reinforcement design in reinforced concrete structures. The reinforcement design process and design phases in the AR_CAD software system are presented. Some examples of application of this system are described. A method of introducing computer supported reinforcement design into design practice is proposed.

TURK Žiga

Object-oriented modelling techniques and integrated CAD

Automation in Construction, 1993, Vol. 1(4): 323-337

ABSTRACT

In integrated CAD different techniques are used to model various features (informations, activities, data and data flow) of the problem domain. Because they model the same real world topic, all aspects developed using different techniques must be compatible and able to co-operate. Since most modelling techniques were developed independently, co-operation is not encouraged. We propose an object oriented modelling approach borrowed from object oriented software design that offers methods and notations for both static and dynamic aspects of state and behaviour of the models and yields smoother development into implementations with object-oriented languages and databases. The paper discusses the motives, the details of the OO modelling approaches and an example from the domain of standards representation. It has been found out that particularly the introduction of the mechanism concept enables and forces us to think about new features of our models.

TURK Žiga

Phenomenological foundations of conceptual product modelling in architecture, engineering and construction

Artificial intelligence in engineering, 2001, Vol. 15: 83-92

ABSTRACT

The ultimate goal of conceptual modelling in architecture, engineering and construction (AEC) has been to define the data structures that could be used to describe the entire built environment throughout all its life cycle stages - from inception and design to demolition. In spite of the magnitude and complexity of this task, the theoretical foundations of modelling received little attention. In this paper, the theoretical foundations of the traditional modelling approaches are questioned. An unorthodox perspective on the computerised representation of the world is introduced. The view is based on phenomenology and hermeneutics. The author exposes the difference between the re-modelling of some existing models, the modelling of physical objects and the modelling of psychical, intentional objects. He suggests that the three categories of "reality" can not be modelled using the same approaches and claims that in developing product models in AEC, the developers should acknowledge that they are modelling intentional objects. The author concludes that AEC or building product and process models do not model objective reality but the modeller's partial intentional understanding of that reality. Therefore, several correct but different models may and should exist. Future software architectures in AEC should not be built on a unified, centralized model but, on a federation of models, which may not be standardised but whose schemas are encoded in a standard way.

TURK Žiga

Multimedia: providing students with real world experiences

Automation in construction, 2001, Vol. 10(2): 247-255

ABSTRACT

Multimedia has been quickly accepted by the engineering community. In the first part of the paper the author provides a theoretical explanation why multimedia is popular in engineering: because it tries to provide an artificial "being-in-the-world" experience. This explanation is backed by Heidegger's philosophy and Winograd's critique of AI. Heidegger believed that humans basically act pre-reflectively, depending on the situation into which they are thrown. Such decisions are based on common sense and intuitive knowledge accumulated while "being-in-the-world", and particularly during breakdowns. Engineering students have few opportunities to observe breakdowns, however, information technology, particularly virtual reality and multimedia provide them.

In the second part of the paper a system to teach earthquake engineering is presented, based on the principles of breakdown oriented learning. The system is built around a multimedia database that contains digitised photographs of damages caused by some of the recent major earthquakes. To a large extent such multimedia tools can replace the learning from real breakdowns and complements theoretical knowledge that can be passed on using traditional means.

DOLENC Matevž

Developing extendible component-oriented finite element software

Advances in engineering software, 2004, Vol. 35: 703-714

ABSTRACT

The component-oriented software development can greatly improve the implementation efficiency and ease the extensibility and maintenance of large engineering software. In this paper, a prototype component-oriented software system for structural analysis using the finite element method is presented. The prototype program is completely based on the Component object model that enables the development of modular, object-oriented, customizable and upgradable, distributed programming systems using a number of different programming languages.

TURK Žiga

Construction informatics: definition and ontology,

Advanced engineering informatics, 2006, Vol. 20(2): 187-199

ABSTRACT

This paper proposes a definition, scope and topics of construction informatics – a discipline also known as “construction IT” or "communication and information technologies in construction". It presents its ontology that, together with methodology, epistemology and axiology, constitutes a formal definition of a scientific field. In philosopy, ontology defines "what exists". In the case of a scientific field - what exists for a discipline, what is its area of discourse. The given ontology of construction informatics has a shape of a hierarchy. On the top level it distinguishes between (1) core themes and (2) support themes. Core themes create knowledge related either to (a) information processing activities, (b) communication/coordination activities or about (c) common infrastructures. The support themes address the knowledge transfer process and include research needs, transfer, deployment and impact of research. The ontology can be used to map a research area, to design a curriculum, to structure the agenda of a conference, to provide keywords and classifications for bibliographic databases or knowledge management in general.

BJORK Bo-Christer, TURK Žiga

The Electronic journal of information technology in construction (ITcon)

Information research, 2006, Vol. 11(3)

ABSTRACT

This case study is based on the experiences with the Electronic Journal of Information Technology in Construction (ITcon), founded in 1995. This journal is an example of a particular category of open access journals, which use neither author charges nor subscriptions to finance their operations, but rely largely on unpaid voluntary work in the spirit of the open source movement. The journal has, after some initial struggle, survived its first decade and is now established as one of half-a-dozen peer reviewed journals in its field. The journal publishes articles as they become ready, but creates virtual issues through alerting messages to “subscribers”. It has also started to publish special issues, since this helps in attracting submissions, and also helps in sharing the work-load of review management. From the start the journal adopted a rather traditional layout of the articles. After the first few years the HTML version was dropped and papers are only published in PDF format.

DOLENC Matevž, KATRANUSCHKOV Peter, GEHRE Alexander, KUROWSKI Krzysztof, TURK Žiga

The InteliGrid platform for virtual organisations interoperability

Journal of information technology in construction: ITcon., 2007, Vol. 12: 459-477

ABSTRACT

The EU project InteliGrid (2004-2007) combined and extended the state-of-the-art research and technologies in the areas of semantic interoperability, virtual organisations and grid technology to provide diverse engineering industries with a platform prototype with flexible, secure, robust, interoperable, pay-per-demand access to information, communication and processing infrastructure. This paper presents some of the key findings and developments related to the semantic grid architecture for virtual organisations and primarily distributed engineering in construction. After a general introduction to the overall vision of the InteliGrid project, the paper presents key identified user roles in the system as well as top end user requirements. This is followed by a description of the system architecture including conceptual, service frameworks and key developed components that the system offers. The paper concludes with a description of an integrated demonstration from the architecture, engineering and construction sector that has been the basis for requirements and validation of the results.

CEROVŠEK Tomo

A review and outlook for a 'Building Information Model' (BIM): a multi-standpoint framework for technological development.

Advanced engineering informatics, 2011, Vol. 25(2): 224-244

ABSTRACT

This study provides a review of critical issues for 'Building Information Modelling' (BIM) tools and standards and suggests comprehensive recommendations for their advancement and development that may improve BIM technologies and provide a basis for advanced inter-operability, integration, model-based communication, and collaboration in building projects.

Based on a critical review of Building Product Modelling, including the development of standards for exchange and the features of technologies and digital models, a methodological framework is proposed for improvements to both BIM tools and schemata. The features relevant to the framework were studied using a conceptual process model and a 'BIM System-of-Systems' (BIM-SoS) model. The development, implementation, and use of the BIM Schema are systemicly analysed from the standpoint of standardisation.

The results embrace the guidelines for a BIM research methodology, with recommended methods and procedures, an R&D review with critique, and a multi-standpoint framework for developments, supported by BIM metrics, upon which the progress of tools, models, and standards may be measured, evaluated, streamlined, and judged. The framework proposes the development of BIM Schema as evolutionary ontology by 'segmented standpoint models' to better account for evolving tools and AEC/O practices.

CEROVŠEK Tomo, MIKOŠ Matjaž

A comparative study of cross-domain research output and citations : research impact cubes and binary citation frequencies

Journal of informetrics, 2014, Vol 8(1):147-161

ABSTRACT

The paper focuses on the meta-study of scientific fields. Across the various scientific domains, significant differences occur with respect to research publishing formats, frequencies and citing practices, the nature and organisation of research and the number and impact of a given domain's academic journals. Consequently, differences occur in the citations and h-indices of the researchers. This paper attempts to identify cross-domain differences using quantitative and qualitative measures. The study focuses on the relationships among citations, authors and meta h-indices across domains and for research group sizes. The analysis is based on the research output of approximately 10,000 researchers in Slovenia, of which we focus on 6536 researchers working in 284 research group programmes in 2008–2012.

As comparative measures of cross-domain research output, we propose the research impact cube (RIC) representation and the analysis of most-cited papers, highest impact factors and citation distribution graphs (Lorenz curves). The analysis of Lotka's model resulted in the proposal of a binary citation frequencies (BCF) distribution model that describes well publishing frequencies.

The results may eventually be used as a model to measure, compare and evaluate fields of science on the global, national and research community level to streamline research policies and evaluate progress over a definite time period.

MEŽA Sebastjan, TURK Žiga, DOLENC Matevž

Component based engineering of a mobile BIM-based augmented reality system

Automation in construction, 2014, Vol. 42(X.) 1-12

ABSTRACT

Over the last decade, building information models (BIM) have become increasingly popular. Yet their use on construction sites where the digital materializes, is limited. A technology that can bridge the gap between the digital and the real world is augmented reality (AR). We analyze this gap and the AR potential and present how the component based software engineering method can be used to efficiently implement a BIM-based AR system for construction. An architecture of the software system is proposed and verified by a prototype which was tested in a real construction project. We found out that the use of AR can significantly narrow the semantic gap between the digital model and the real world; that components for creating a BIM-based AR systems exist but currently do not scale well to large models; and that the use in AR applications creates additional requirements the for BIM models and tools, particularly related to the BIM's 4th dimension.

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TURK Žiga

Ten questions concerning building information modelling

Building and environment, 2016, Vol. 107: 274-284

ABSTRACT

Building information modelling (BIM) has been a dominant topic in information technology in construction research since this memorable acronym replaced the boring “product modelling in construction” and the academic “conceptual modelling of buildings”. The ideal of having a complete, coherent, true digital representation of buildings has become a goal of scientific research, software development and industrial application. In this paper, the author asks and answers ten key questions about BIM, including what it is, how it will develop, how real are the promises and fears of BIM and what is its impact. The arguments in the answers are based on an understanding of BIM that considers BIM in the frame of structure-function-behavior paradigm. As a structure, BIM is a database with many remaining database challenges. The function of BIM is building information management. Building information was managed before the invention of digital computers and is managed today with computers. The goal is efficient support of business processes, such as with database-management systems. BIM behaves as a socio-technical system; it changes institutions, businesses, business models, education, workplaces and careers and is also changed by the environment in which it operates. Game theory and institutional theory provide a good framework to study its adoption. The most important contribution of BIM is not that it is a tool of automation or integration but a tool of further specialization. Specialization is a key to the division of labor, which results in using more knowledge, in higher productivity and in greater creativity.

TURK Žiga, KLINC Robert

Potentials of blockchain technology for construction management.

Procedia engineering, 2017, Vol. 196: 638-645

ABSTRACT

Blockchain technology enables distributed, encrypted and secure logging of digital transactions. It is the underlying technology of Bitcoin and other cryptocurrencies. Blockchain is expected to revolutionize computing in several areas, particularly where centralization was unnatural and privacy was important. In the paper, we present research on where and how this technology could be useful in the construction industry. The work is based on the study of literature on open issues that exist in construction process management. These are than matched to the capabilities of blockchain. We are motivated by the fact that construction projects involve a dynamic grouping of several companies. We study the degree to which the relationships among them are hierarchical or peer-to-peer and note that particularly in information intensive phases, centralization of information management was necessary because of technology. When using un-constraining technology, communication patterns among participants show a peer-to-peer nature of the relationships. In such environment, blockchain can provide a trustworthy infrastructure for information management during all building life-cycle stages. Even if building information modelling (BIM) is used, which assumes a centralized building information model, there is a role for blockchain to manage information on who did what and when and thus provide a basis for any legal arguments that might occur. On the construction site blockchain can improve the reliability and trustworthiness of construction logbooks, works performed and material quantities recorded. In the facility maintenance phase, blockchain's main potential is the secure storage of sensor data which are sensitive to privacy. We conclude that blockchain provides solutions to many current problems in construction information management. However, it is more likely that it will be built into generic IT infrastructure on top of which construction applications are built, rather than used directly by authors of construction related software. It has a potential to make construction processes less centralized which opens needs for research in that direction.

KLINC Robert, TURK Žiga

Construction 4.0 - digital transformation of one of the oldest industries

Economic and business review, 2019, Vol. 21(3): 393-410

ABSTRACT

In the early 2010s, the German industry started their reform and revival under the keyword "Industrie Vier Punkt Null". The European Union's strategies adopted most of the ideas and member states followed. The European construction industry too stared to explore how to benefit from it. In this review paper, we explain the ideas behind Industry 4.0. We present aspects of Industry 4.0: what it means for the customer, business and industry as a whole. Based on that framework we analysed the potentials of Industry 4.0 in the construction industry and where – due to some specifics of the industry – construction is actually ahead in adopting the Industry 4.0 concepts.

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STEGNAR Gašper, CEROVŠEK Tomo

Information needs for progressive BIM methodology supporting the holistic energy renovation of office buildings

Energy, 2019, Vol. 173: 317-331

ABSTRACT

The paper presents digital methodology that can gradually and efficiently streamline the energy renovation of office buildings. The focus is on the use of Building Information Modelling (BIM) and energy simulations to facilitate informed decision-making in refurbishment process of office buildings. The study targets better project information management to meet the information needs of energy renovation design, performance evaluation, (re)construction and on-field operations.

Ineffectively managed information often leads to sub-standard project deliverables, re-work, errors, budget deficits, and delays. Proposed progressive BIM methodology establishes a framework to adequately manage information to match the purpose of an evolving renovation design process and project lifecycle - with emphasis on energy performance - while addressing multiple aspects of sustainability in built environment. This approach is based on firm methodological principles and validated on the actual refurbishment of office buildings.

Results show that progressive BIM methodology can improve design, more accurately predict energy consumption, reduce investment costs, prevent design and planning errors, and prevent construction delays. This study is a valuable contribution to renovation design research and development, especially to practitioners (architects and engineers) and in terms of alignment of client requirements and actual project outcomes. The underlying key principle is clear profiling of the information requirements for different levels of refurbishment design services and renovation activities.

TURK Žiga, KLINC Robert

A social-product-process framework for construction

Building research and information, 2020, Vol. 48(7): 747-762

ABSTRACT

This paper introduces a new framework for understanding, modelling and software engineering in construction information activities. The current framework is based on understanding that products are the results of processes, which are performed by actors. Such frameworks are influenced by the available technology. The Internet of today is supporting also other kinds of human activities: communication and social interactions among humans. The construction industry uses them as well but without having a proper understanding of their role. There is a gap in the current framework. In this paper, the relevant theories to specify this gap in terms of what could exist in theory and what is offered by technology are analysed. As a result, a new framework of construction information activities that fills the gap is proposed. The key concepts and relations among them are identified and elaborated within the existing framework. The framework introduces the third major integrative element of the otherwise fragmented construction information activities –the social network –the existing two being the physical building and its digital twin. The framework provides a theoretical and conceptual basis for designing, planning, creating, monitoring and evaluating construction-related online services that include a strong social component and use social media services.

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TURK Žiga

Interoperability in construction - mission impossible?

Developments in the built environment, 2020, Vol. 4/100018: 1-9

ABSTRACT

Throughout the history of human civilization, specialization and division of labour have been key factors of progress. They were made possible by the cooperation of ever-larger groups of people. Construction has been no exception. However, specialization leads to fragmentation - unless specialization is supported by approaches and technologies that enable people to work together and that systems are interoperable. When it comes to interoperability, the construction sector is often considered special, but it is not incomparable to other industries. Methodologically, this paper is based on the frameworks developed in the field of Enterprise Information Systems. It considers interoperability as a means to achieve a goal. Novel is the understanding that the ultimate goal is neither integration nor more efficient construction but rather the division of labour and specialization. A comparison of approaches to interoperability with those in other areas reveals some gaps. Research in construction information technology has focused on one type of interoperability - semantic interoperability - intending to achieve computer integrated construction. There are other types of interoperability - legal and organizational - and other levels of interoperability - federated and unified. These also deserve investigation. In the future, there will be a growing number of systems that would need to be made interoperable, especially in connection with the construction 4.0's Internet of Things, sensors, intelligent systems, etc. Since interoperability problems are caused by the emerging specializations, the problems of interoperability will never go away. The industry will have to recognize that it will always operate in an environment where interoperability is challenged. While research will continue working towards making systems interoperable and integrated it would need also to give attention to exploring collaboration in environments that are only partially interoperable.

TURK Žiga, GARCIA DE SOTO Borja, MANTHA Bharadwaj, MACIEL Abel, GEORGESCU Alexandru

A systemic framework for addressing cybersecurity in construction

Automation in construction, 2022, Vol. 133(art. 103988): 14 pp.

ABSTRACT

Today, the built environment is designed, built, and managed using digital technology, making it increasingly exposed to cyber security risks. Cybersecurity is a general topic, and the construction sector has been borrowing general solutions and frameworks. However, the construction industry is specific and needs a specialized framework that would advise how to understand and manage cybersecurity. We have studied general cybersecurity frameworks, cybersecurity standards, research literature, and first principles of systems theory and process engineering. Drawing from that, we developed an original framework that identifies three kinds of wrongful activities: stealing, lying, and harming. It identifies four elements that can be affected by wrongful activities: information asset, material asset, person, and system. It defines cybersecurity as the absence of the three wrongs across the four kinds of elements. The framework is construction-specific, and as such, a useful tool for senior management to understand security problems and organize security processes. It can lead to better standardization and also helps the researchers to structure future work on the topic. The latter should be concentrated in areas where construction was found to be different: the dynamic and overlapping process and organizational boundaries in the design stage, the exposed shared design information, and the vulnerability of control information of the built environment, particularly in the critical infrastructures.

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BRANK Boštjan, PERIĆ Djordje, DAMJANIĆ Frano

On implementation of a nonlinear four node shell finite element for thin multilayered elastic shells.

Computational mechanics, 1995, Vol. 16(5): 341-359

ABSTRACT

A simple non-linear stress resultant four node shell finite element is presented. The underlying shell theory is developed from the three dimensional continuum theory via standard assumptions on the displacement field. A model for thin shells is obtained by approximating terms describing the shell geometry. In this work the rotation of the shell director is parameterized by the two Euler angles, although other approaches can be easily accommodated. A procedure is provided to extend the presented approach by including the through-thickness variable material properties. These may include a general non-linear elastic material with varied degree of orthotropy, which is typical for fibre reinforced composites. Thus a simple and efficient model suitable for analysis of multilayered composite shells is attained. Shell kinematics is consistently linearized, leading to the Newton-Raphson numerical procedure, which preserves quadratic rate of asymptotic convergence. A range of linear and non-linear tests is provided and compared with available solutions to illustrate the approach.

BRANK Boštjan, PERIĆ Djordje, DAMJANIĆ Frano

On large deformations of thin elasto-plastic shells: implementation of a finite rotation model for quadrilateral shell element

International journal for numerical methods in engineering, 1997, Vol. 40: 689-726.

ABSTRACT

A large-deformation model for thin shells composed of elasto-plastic material is presented in this work. Formulation of the shell model, equivalent to the two-dimensional Cosserat continuum, is developed from the three-dimensional continuum by employing standard assumptions on the distribution of the displacement field in the shell body. A model for thin shells is obtained by an approximation of terms describing the shell geometry. Finite rotations of the director field are described by a rotation vector formulation. An elasto-plastic constitutive model is developed based on the von Mises yield criterion and isotropic hardening. In this work, attention is restricted to problems where strains remain small allowing for all aspects of material identification and associated computational treatment, developed for small-strain elastoplastic models, to be transferred easily to the present elasto-plastic thin-shell model. A finite element formulation is based on the four-noded isoparametric element. A particular attention is devoted to the consistent linearization of the shell kinematics and elasto-plastic material model, in order to achieve quadratic rate of asymptotic convergence typical for the Newton-Raphson-based solution procedures.

DOLINŠEK Blaž, DUHOVNIK Janez

Robotic assembly of rebar cages for beams and columns

Automation in construction, 1998, Vol. 8(2): 195-207

ABSTRACT

In the paper, the design and method of operation of a robot cell for the assembly of rebar cages for beams and columns is described. The input elements are pre-manufactured rebars, and the output consists of rebar cages. Inside the robot cell, assembly is performed by robots equipped with tools for grasping the rebars, tools for bending the stirrups, and tools for welding the stirrups to the longitudinal bars. Various mechanisms for supplying the robots with rebars and supporting them during the assembly process have also been designed. Because of the specific nature of the assembly process, where robots have to successfully avoid various obstacles, mass-produced robots cannot be used for the assembly of rebar cages. For this reason, special robot configurations have to be designed. The robot cell described in this paper is at present at the design stage. It was modelled and simulated using the program workspace 3 for robot simulation, which makes it possible to study, optimise, and design in detail the proposed robot systems. The figures in the paper describing how such a system works have also been taken from this simulation.

BRANK Boštjan, BRISEGHELLA Lamberto, TONELLO Nicola, DAMJANIĆ Frano.

On non-linear dynamics of shells : implementation of energy-momentum conserving algorithm for a finite rotation shell model

International journal for numerical methods in engineering, 1998, Vol. 42: 409-442.

ABSTRACT

Continuum and numerical formulations for non-linear dynamics of thin shells are presented in this work. An elastodynamic shell model is developed from the three-dimensional continuum by employing standard assumptions of the first-order shear-deformation theories. Motion of the shell-directior is described by a singularity-free formulation based on the rotation vector. Temporal discretization is performed by an implicit, one-step, second-order accurate, time-integration scheme. In this work, an energy and momentum conserving algorithm, which exactly preserves the fundamental constants of the shell motion and guaranties unconditional algorithmic stability, is used. It may be regarded as a modification of the standard mid-point rule. Spatial discretization is based on the four-noded isoparametric element. Particular attention is devoted to the consistent linearization of the weak form of the initial boundary value problem discretized in time and space, in order to achieve a quadratic rate of asymptotic convergence typical for the Newton-Raphson based solution procedures. An unconditionally stable time finite element formulation suitable for the long-term dynamic computations of flexible shell-like structures, which may be undergoing large displacements, large rotations and large motions is therefore obtained. A set of numerical examples is presented to illustrate the present approach and the performance of the isoparametric four-noded shell finite element in conjunction with the implicit energy and momentum conserving time-integration algorithm.

SHIFRIN Efim, BRANK Boštjan, SURACE Giuseppe

Analytical-numerical solution of elliptical interface crack problem

International journal of fracture, 1998, Vol. 94(1-4): 201-215

ABSTRACT

The problem of elliptical interface crack, located between two bonded dissimilar elastic half spaces, is considered. To obtain a solution of the problem, the traction boundary pseudodifferential equations are used. An analytical-numerical method for solving these equations is proposed. Strain energy release rates along the crack contours are calculated for some examples

BRANK Boštjan, CARRERA Erasmo

Multilayered shell finite element with interlaminar continuous shear stresses : a refinement of the Reissner-Mindlin formulation

International journal for numerical methods in engineering, 2000, Vol. 48(6): 843-874

ABSTRACT

A finite element formulation for refined linear analysis of multilayered shell structures of moderate thickness is presented. An underlying shell model is a direct extension of the first-order shear-deformation theory of Reissner-Mindlin type. A refined theory with seven unknown kinematic fields is developed; (i) by introducing an assumption of a zig-zag (i..e. layer-wise linear) variation of displacement field through the thickness, and (ii) by assuming an independent transverse shear stress fields in each layer in the framework of Reissner's mixed varianational principle. The introduced transverse shear stress unknowns are eliminated on the cross-section level. At this process, the interlaminar equilibrium conditions (i.e. the interlaminar shear stress continuity continuity conditions) are imposed. As a result, the weak form of constitutive equations (the so-called weak form of Hooke's law) is obtained for the transverse strains-transverse stress resultants relation. A finite element approximation is based on the four-noded isoparametric element. To eliminate the shear locking effect, the assumed strain variational concept is used. Performance of the derived finite element is illustrated with some numerical examples. The results are compared with the exact three-dimensional solutions, as well as with the analytical and numerical solutions obtained by the classical, the first-order and some representative refined models.

KEGL Marko, BRANK Boštjan

Shape optimization of truss-stiffened shell structures with variable thickness

Computer methods in applied mechanics and engineering, 2006, Vol. 195(19/22): 2611-2634.

ABSTRACT

This paper presents an effective approach to shape optimal design of statically loaded elastic shell-like structures. The shape parametrization is based on a design element technique. The chosen design element is a rational Bézier body, enhanced with a smoothly varying scalar field. A body-like design element makes possible to unify the shape optimization of both pure shells and truss-stiffened shell structures. The scalar field of the design element is obtained by attaching to each control point a scalar quantity, which is an add-on to the position and weight of the control point. This scalar field is linked to the shell thickness distribution, which can be optimized simultaneously with the shape of the shell. For linear and non-linear analysis of shell structures, a reliable 4-node shell finite element formulation is utilized. The presented optimization approach assumes the employment of a gradient-based optimization algorithm and the use of the discrete method of direct differentiation to perform the sensitivity analysis. Four numerical examples of shell and truss-stiffened shell optimization are presented in detail to illustrate the performance of the proposed approach.

KEGL Marko, BRANK Boštjan, HARL Boštjan, OBLAK Maks

Efficient handling of stability problems in shell optimization by asymmetric "worst case" shape imperfection

International journal for numerical methods in engineering, 2008, Vol. 73(9): 1197-1216

ABSTRACT

The paper presents an approach to shape optimization of proportionally loaded elastic shell structures under stability constraints. To reduce the stability-related problems, a special technique is utilized, by which the response analysis is always terminated before the first critical point is reached. In this way, the optimization is always related to a precritical structural state. The necessary load-carrying capability of the optimal structure is assured by extending the usual formulation of the optimization problem by a constraint on an estimated critical load factor. Since limit points are easier to handle, the possible presence of bifurcation points is avoided by introducing imperfection parameters. They are related to an asymmetric shape perturbation of the structure. During the optimization, the imperfection parameters are updated to get automatically the 'worst-case' pattern and amplitude of the imperfection. Both, the imperfection parameters and the design variables are related to the structural shape via the design element technique. A gradient-based optimizer is employed to solve the optimization problem. Three examples illustrate the proposed approach.

DUJC Jaka, BRANK Boštjan, IBRAHIMBEGOVIĆ Adnan

Multi-scale computational model for failure analysis of metal frames that includes softening and local buckling

Computer methods in applied mechanics and engineering, 2010, Vol. 199(21-22): 1371-1385

ABSTRACT

In this work we present a new modelling paradigm for computing the complete failure of metal frames by combining the stress-resultant beam model and the shell model. The shell model is used to compute the material parameters that are needed by an inelastic stress-resultant beam model; therefore, we consider the shell model as the meso-scale model and the beam model as the macro-scale model. The shell model takes into account elastoplasticity with strain-hardening and strain-softening, as well as geometrical nonlinearity (including local buckling of a part of a beam). By using results of the shell model, the stress-resultant inelastic beam model is derived that takes into account elastoplasticity with hardening, as well as softening effects (of material and geometric type). The beam softening effects are numerically modelled in a localized failure point by using beam finite element with embedded discontinuity. The original feature of the proposed multi-scale (i.e. shell-beam) computational model is its ability to incorporate both material and geometrical instability contributions into the stress-resultant beam model softening response. Several representative numerical simulations are presented to illustrate a very satisfying performance of the proposed approach.

DUJC Jaka, BRANK Boštjan

Stress resultant plasticity for shells revisited

Computer methods in applied mechanics and engineering, 2012, Vol. 247/248: 146-165

ABSTRACT

In this work, we revisit the stress resultant elastoplastic geometrically exact shell finite element formulation that is based on the Ilyushin–Shapiro two-surface yield function with isotropic and kinematic hardening. The main focus is on implicit projection algorithms for computation of updated values of internal variables for stress resultant shell elastoplasticity. Four different algorithms are derived and compared. Three of them yield practically identical final results, yet they differ considerably in computational efficiency and implementation complexity, since they solve different sets of equations and they use different procedures that choose active yield surfaces. One algorithm does not provide acceptable accuracy. It turns out that the most simple and straightforward algorithm performs surprisingly well and efficiently. Several numerical examples are presented to illustrate the Ilyushin–Shapiro stress resultant shell formulation and the numerical performance of the presented integration algorithms.

JUKIĆ Miha, BRANK Boštjan, IBRAHIMBEGOVIĆ Adnan

Embedded discontinuity finite element formulation for failure analysis of planar reinforced concrete beams and frames.

Engineering structures, 2013, Vol. 50(5): 115-125

ABSTRACT

An Euler–Bernoulli stress resultant beam finite element for static collapse analysis of planar reinforced concrete beams and frames is presented in detail. The pre-failure inelastic effects are described by the (axial force dependent) bending elastoplasticity with bi-linear isotropic hardening. To capture the response of the beam after the localized failure of the critical cross-section, the softening plastic hinge is incorporated at the location of the failure. The dissipative effects of the softening hinge are introduced into the finite element formulation by enhanced kinematics, with singular curvature in the softening hinge, within the framework of finite elements with embedded strong discontinuities. The implementation details of the finite element formulation are provided. Several numerical examples are presented to illustrate the performance of the element.

BOHINC Uroš, BRANK Boštjan, IBRAHIMBEGOVIĆ Adnan

Discretization error for the Discrete Kirchoff plate finite element approximation

Computer methods in applied mechanics and engineering, 2014, Vol. 269: 415-436,

ABSTRACT

We provide in this work the discretization error estimates that can guide an adaptive mesh refinement for the Discrete Kirchhoff plate finite elements. The proposed developments are built upon the concept of error estimates for classical elasticity and adapted to suit the Kirchhoff plate finite elements. We give a detailed illustration of the proposed procedures for the Discrete Kirchhoff triangular plate element, along with several different possibilities for constructing the enhancement of test space needed for error estimates. The first novelty concerns the consistent displacement field in terms of the third order polynomial for the Discrete Kirchhoff triangle, whereas the second novelty is the use of the Argyris triangle with fifth order polynomials for constructing the enhanced test for error estimates. We compare the latter against several alternatives that can be used for Kirchhoff plates. The results of numerical examples are given to illustrate the effectiveness of proposed discretization error estimates.

JUKIĆ Miha, BRANK Boštjan, IBRAHIMBEGOVIĆ Adnan

Failure analysis of reinforced concrete frames by beam finite element that combines damage, plasticity and embedded discontinuity

Engineering structures, 2014, Vol. 75(Sept.): 507-527

ABSTRACT

We present a multi-layer beam finite element formulation for failure analysis of planar reinforced concrete beams and frames, which is based on the Timoshenko beam model. Material behavior of the concrete and the steel layer is described by an elasto-damage and an elasto-plastic material model, respectively. In order to be able to describe the fracture energy, a layer-wise application of the embedded discontinuity concept is adopted. In particular, a jump in the layer-axial-displacement is embedded into the standard beam kinematics when the layer stress state fulfills the material failure criterion and the layer functions in the softening phase. This allows applying a softening-damage and a softening-plasticity traction-separation cohesive law in concrete and steel layers, respectively. The computer code implementation is described in detail. A set of numerical examples is presented in order to illustrate an ability of the formulation to model and compute failure response of reinforced concrete beams and frames under monotonic static loading. Finally, the formulation is critically assessed.

STANIĆ Andjelka, BRANK Boštjan

A path-following method for elasto-plastic solids and structures based on control of plastic dissipation and plastic work

Finite elements in analysis and design, 2017, Vol. 123(1): 1-8

ABSTRACT

A path-following method that is based on controlling plastic dissipation or plastic work in an inelastic solid or structure is presented. It can be effective for highly nonlinear materially and geometrically problems. In particular, it can be applied for elasto-plastic problems where the standard arc-length methods fail, or to avoid artificial and undesirable elastic unloading of a complete solid or structure during the computation. The essential ingredients, the plastic dissipation and the plastic work based constraint equations, are derived by using either explicit or implicit pseudo-time step integration. These constraint equations are valid for geometrically nonlinear small strain elasto-plasticity with hardening. Their implementation in the framework of the path-following method is described. Several numerical examples are presented in order to illustrate very satisfying performance of the derived path-following method. It performed very well for some challenging shell problems.

VEDLIN Tomo, LAVRENČIČ Marko, BRANK Boštjan, BROJAN Miha

A comparison of computational models for wrinkling of pressurized shell-core systems

International journal of non-linear mechanics, 2020, Vol. 127, 103611

ABSTRACT

Four nonlinear computational models for the surface wrinkling of curved shell-core systems under external pressure are presented. Three of the considered finite element models neglect the displacements tangential to the shell surface. Two of the models are static formulations and the other two are derived in the dynamic framework. For the latter, the energy-decaying time-stepping algorithm is applied, which is suitable for numerically stiff problems, such as shell-core systems, characterized by stiff membrane and soft wrinkling deformation modes. In all cases the core is modeled by elastic springs. As a comparative problem we choose the surface wrinkling of pressurized shell-core spheres. In particular, five systems with different material and geometric properties are computed, which have different wrinkle patterns. A good agreement is found between the results of the models as well as with the relevant references, which provide numerical and experimental results. However, it has been observed that our reduced-order models are blind to the prediction of the secondary transformation - from the dimple-like pattern to the labyrinthine pattern. Another conclusion is that a non-tailored (i.e. standard) shell finite element on an elastic foundation combined with the energy-decaying scheme, provides excellent predictions of the surface wrinkle patterns.

LAVRENČIČ Marko, BRANK Boštjan

Hybrid-mixed low-order finite elements for geometrically exact shell models: overview and comparison

Archives of computational methods in engineering, 2021, Vol. 28: 3917-3951

ABSTRACT

We critically review and compare ffteen mixed and mixed-hybrid nonlinear shell fnite element formulations with 4 nodes in order to identify those that are closest to the "optimal" one. We consider formulations that are based either on Assumed Natural Strain concept, Enhanced Assumed Strain concept, Hellinger-Reissner functional or Hu-Washizu functional, and those that efectively combine several of the mentioned approaches. Most of the formulations are state-of-the-art, but some are also presented for the frst time. We show that the fexibility of mixed-hybrid formulations requires careful consideration of theoretical and numerical aspects in the process of design of a high-performance element. We make extensive numerical experiments in order to assess convergence properties, mesh distortion sensitivity, and computational speed (that is associated with the ability to achieve large steps during the solution search) of the considered formulations. We show that the application of the idea to combine mixed-hybrid formulations of the Hellinger-Reissner and Hu-Washizu type with the Assumed Natural Strain and/or the Enhanced Assumed Strain concepts generates the formulations that perform excellent. We also identify the formulations that are currently closest to the "optimal" one.

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Model updating of seven-storey cross-laminated timber building designed on frequency-responsefunctions-based modal testing.

Structure and infrastructure engineering. 2021, DOI: 10.1080/15732479.2021.1931893

ABSTRACT

Based on the experimental estimation of the key dynamic properties of a seven-storey building made entirely of cross-laminated timber (CLT) panels, the finite element (FE) model updating was performed. The dynamic properties were obtained from an input-output full-scale modal testing of the building in operation. The chosen parameters for the FE model updating allowed the consideration of the timber connections in a smeared sense. This approach led to an excellent match between the first six experimental and numerical modes of vibrations, despite spatial aliasing. Moreover, it allowed, together with the sensitivity analysis, to estimate the stiffness (affected by the connections) of the building structural elements. Thus, the study provides an insight into the as-built stiffness and modal properties of tall CLT building. This is valuable because of the currently limited knowledge about the dynamics of tall timber buildings under service loadings, especially because their design is predominantly governed by the wind-generated vibrations.

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STANIĆ Andjelka, BRANK Boštjan, IBRAHIMBEGOVIĆ Adnan, MATTHIES Hermann

Crack propagation simulation without crack tracking algorithm - embedded discontinuity formulation with incompatible modes

Computer methods in applied mechanics and engineering, 2021, Vol. 386(114090): 1-39

ABSTRACT

We show that for the simulation of crack propagation in quasi-brittle, two-dimensional solids, very good results can be obtained with an embedded strong discontinuity quadrilateral finite element that has incompatible modes. Even more importantly, we demonstrate that these results can be obtained without using a crack tracking algorithm. Therefore, the simulation of crack patterns with several cracks, including branching, becomes possible. The avoidance of a tracking algorithm is mainly enabled by the application of a novel, local (Gauss-point based) criterion for crack nucleation, which determines the time of embedding the localisation line as well as its position and orientation. We treat the crack evolution in terms of a thermodynamical framework, with softening variables describing internal dissipative mechanisms of material degradation. As presented by numerical examples, many elements in the mesh may develop a crack, but only some of them actually open and/or slide, dissipate fracture energy, and eventually form the crack pattern. The novel approach has been implemented for statics and dynamics, and the results of computed difficult examples (including Kalthoffs test) illustrate its very satisfying performance. It effectively overcomes unfavourable restrictions of the standard embedded strong discontinuity formulations, namely the simulation of the propagation of a single crack only. Moreover, it is computationally fast and straightforward to implement. Our numerical solutions match the results of experimental tests and previously reported numerical results in terms of crack pattern, dissipated fracture energy, and load displacement curve.

LAVRENČIČ Marko, BRANK Boštjan

Energy-decaying and momentum-conserving schemes for transient simulations with mixed finite elements

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ABSTRACT

We present the four-field (of displacements, velocities, stresses and strains) and the three-field (of displacements, velocities and stresses) mixed variational formulations for structural dynamics, which can be used to derive in an elegant way the energy-decaying and momentum-conserving (EDMC) time-stepping schemes for transient simulations with mixed solid and structural finite elements. These mixed variational formulations are in this work applied for the derivation of EDMC schemes for the geometrically exact, recently proposed, mixed-hybrid, shell finite elements (with excellent performance), which combine mixed interpolations of the Hu Washizu type or the Hellinger Reissner type with the assumed natural strain concept. To this end, the first-order and the second-order accurate EDMC schemes are designed. The superior properties of the considered mixed-hybrid shell finite elements, which are reflected in statics by excellent convergence properties, ability to take very large solution steps, and low-sensitivity to mesh distortion, are in this manner extended for (long-term) transient simulations. Numerical examples, which illustrate transient simulations with the EDMC schemes and mixed-hybrid shell finite elements, show (among other effects) that the underlying structure of the shell motion is numerically preserved even for very large time steps.

DUJC Jaka, BRANK Boštjan

Combining coupled, staggered and uncoupled solution methods for phase-field-based fracture analysis

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ABSTRACT

A unified framework for an impromptu switching between the coupled (i.e., the monolithic), the staggered, and the uncoupled solution strategies for the phase-field based computations of material fracture is presented. As a model problem, a 2d quasi-brittle solid phase-field formulation, which is based on the tension-compression split energy functional, is chosen. In order to fit within the proposed framework, the classical staggered approach is reformulated as a loop of uncoupled monolithic steps that we call modified-staggered. Numerical examples show that an automatic switching between the coupled and the modified-staggered solution methods (when the former fails) may shorten the computational times (compared to the pure staggered approach) for an order of magnitude.