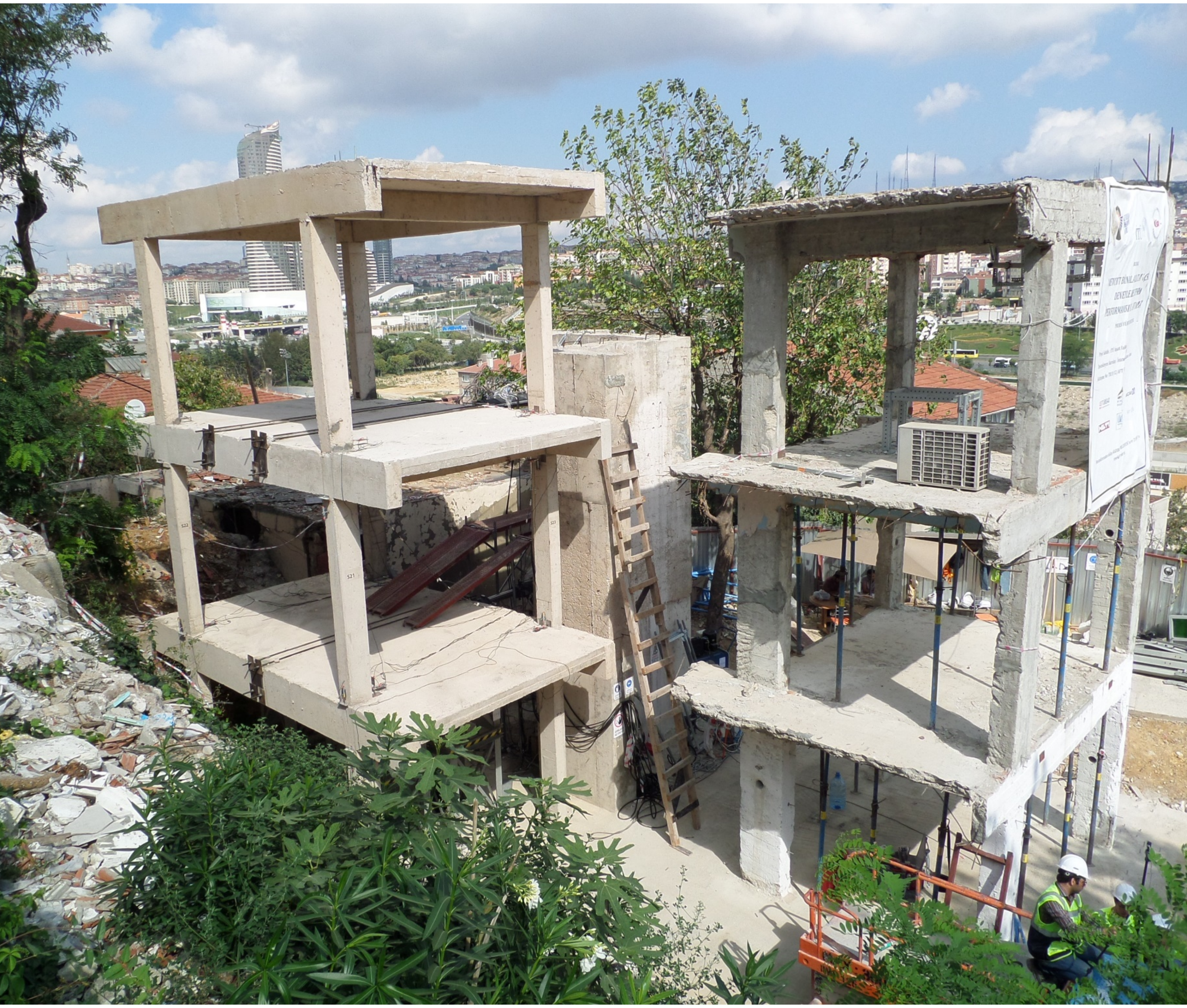
ITU-ISTKA Project

"Determination of the Seismic Performance of the Existing Building by Full Scale Tests"



International Workshop on

Large-scale and/or On-site Structural Testing

for

Seismic Performance Assessment

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Istanbul Technical University

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PREFACE

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SPEAKERS

Stefano Pampanin is Professor of Structural Design & Earthquake Eng. at the Department of Civil and Natural Resources Eng. at the University of Canterbury, Christchurch, New Zealand (NZ), where he joined in 2002. He is Immediate Past President of the NZ Society for Earthquake Eng., NZSEE, (2012-2014). In the past years, he has been dedicating a significant effort in the research and development, codification and practical implementation, as well as knowledge-dissemination, of innovative solutions for the seismic design of low-damage structural systems in concrete or timber, as well as for the seismic retrofit of existing RC structures. He has been actively involved in a number of national and international code and technical committees for the preparation of design guidelines, state-of-art, guides for good practice guides and/or design standards on reinforced concrete, precast and prestressed concrete, assessment and retrofit, prestressed timber. He is author of more than 300 scientific publications in the field of earthquake engineering and received several awards for his research activities.

Koichi Kusunoki is Associate Professor at Earthquake Research Institute, the University of Tokyo. He obtained his Doctor of Engineering at University of Tokyo in 1997. His research interests are in the field of earthquake engineering, building structure, reinforced concrete, structural health monitoring. He is a member of Architectural Institute of Japan, Japan Concrete Institute, Japan Association for Earthquake Eng., Japan Society of Seismic Isolation and an officer of IAEE central office.

Toshimi Kabeyasawa is Professor at Earthquake Research Institute, the University of Tokyo. He obtained his Doctor of Engineering at University of Tokyo in 1985. His research interests are in the field of earthquake eng., building structure, reinforced concrete. He served as a chairman or member of significant professional or academic committees in MLIT, MEXT, MITI, BRI, NIED, RIEF, AIJ, BCJ, JBDPA, JSSI, JEES, GBRC and local governments in Japan. He was the leader for the reconnaissance team of the Architectural Institute of Japan after Kocaeli Earthquake in 1999, which were organized in collaboration with the teams of ITU, METU, BOUN, and KOERI.

Paolo Negro holds a Laurea degree from the University of Padua, a Master of Science in Earthquake Eng. from the University of California at Berkeley and a PhD in Civil Eng. from the University of Wales at Swansea. Before joining the team of the European Laboratory for Structural Assessment (ELSA) of the Joint Research Centre (JRC) of the European Commission (EC) in 1991, he has been working as a structural engineer. At ELSA he has been leading the experimental activities for many EC-funded research projects, including many projects on precast structures. He has been the scientific coordinator for the project Seismic PErformance Assessment and Rehabilitation of existing buildings (SPEAR). He is serving as EU-liaison member in ISO TC 71, Concrete, Reinforced Concrete and Prestressed Concrete, in the Technical Committee TC13, Seismic Design of the European Convention for Constructional Steelwork and in the Management Committee of COST Action C25, Sustainability of Construction. He is serving as vice-president in the International Association for Experimental Structural Eng. He is author or co-author of more than 100 publications in journals and international conferences and is teaching a graduate course on experimental methods at the Polytechnic of Milan.

Jin-Guang Teng holds the positions of Chair Professor of Structural Eng. and Director of Research Institute for Sustainable Urban Development (RISUD) at The Hong Kong Polytechnic University. His research interests include the structural use of fibre-reinforced polymer (FRP) composites in construction and thin-walled structures. His research has led to over 170 SCI journal papers, and has impacted significantly on relevant design codes/guidelines in China, Australia, Europe and the United States. He is a Fellow of the Hong Kong Academy of Eng. Sciences as well as the Hong Kong Institution of Engineers, and served as the founding President of the International Institute for FRP in Construction (IIFC) from 2003 to 2006. He has received a number of prestigious awards for his research contributions, including the Natural Science Award from the State Council of China, Distinguished Young Scholar Award from the Natural Science Foundation of China, the IIFC Medal from the International Institute for FRP in Construction (IIFC), and the State-of-the-Art of Civil Eng. Award from the American Society of Civil Engineers.

Stathis Bousias is Associate Professor at the Department of Civil Eng. of the University of Patras. He obtained his diploma in Civil Eng. from the University of Patras (1985), MSc degree in Civil Eng. from Case Western Reserve University (1987) and PhD degree from the University of Patras (1993). At the University of Patras he has been leading the experimental activities for many EC-and nationally funded research projects, including hybrid testing of full scale structures. He specializes in the experimental testing of structures and development of testing techniques. He has spent several years in R&D at several European laboratories (the European Laboratory for Structural Assessment (ELSA) at the JRC, Ispra, the Portugese National Laboratory of Civil Eng. (LNEC) and the Dynamics Laboratory of ISMES Institute). He is the author of 5 chapters in books, about 60 papers in journals and international conference proceedings. He is member of national and international scientific associations and reviewer for more than 15 international journals. He is also member of the Working Group: Design examples for the application of Strut-and-Tie models in *fib's* TG1.1: Design applications, of the Working Group WG7: Earthquake Resistant Structures of International Association of Bridge and Structural Engineering (IABSE). He serves on the editorial board of the Structural Eng. International journal of IABSE and is member of the Board of the International Association of Experimental Structural Eng. (IAESE).

Cem Demir is a researcher at the Department of Civil Eng. at Istanbul Technical University. He graduated from Istanbul Technical University in 2001, and received his MS (2005) and PhD (2012) degrees from the same university in the field of Structural Engineering. He studied at Akita Prefectural University (Japan) as a visiting scholar. Dr. Demir's research interests include laboratory and site tests on reinforced concrete and masonry structural systems, seismic assessment and retrofitting of existing structures, post-earthquake damage assessment, structural applications of FRPs, and seismic behavior of heritage structures. He is a member of Turkish Chamber of Civil Engineers (IMO), IMO Commission for Disaster Preparedness and Response) and International Institute for FRP in Construction (IIFC).

Ufuk Yazgan is Assistant Proffesor at Earthquake Eng. and Disaster Management Institute, Istanbul Technical University. He obtained his Ph.D. degree in structural engineering from Swiss Federal Institute of Technology, ETH Zurich in 2009. He got his M.S. and B.S. degrees in civil engineering from Middle East Technical University in 2003 and 2001, respectively. He worked as a Research Engineer in the Risk Modelling R&D team of Swiss Reinsurance Co. in Zurich. His research interests cover probabilistic methods in earthquake engineering, simulation of nonlinear response of RC structures, seismic fragility assessment, reliability analysis and structural dynamics. He is experienced in the development of probabilistic seismic damage evaluation methods; empirical vulnerability modelling; seismic vulnerability assessment of structures and seismic hazard assessment.

Serdar Soyöz is Assoc. Proffesor at Department of Civil Eng., Bogazici University. He obtained his Ph.D. degree in structural eng. from University of California Irvine in 2007. He got his M.S. and B.S. degrees in civil eng. from Middle East Technical University in 2004 and 2001, respectively. He worked as a Senior Staff Engineer at MMI Eng., CA for two years. He has also been in Japan for one year as a visiting scholar. His research interests cover structural health monitoring, structural reliability assessment, earthquake eng., structural dynamics and structural control. He is experienced in the development and experimental verification of vibration-based damage detection methodologies; development and implementation of hardware and software systems for structural health monitoring applications; structural reliability estimation methodologies based on system identification results; modeling and implementation of adaptive base isolation technologies; reliability-based code development of wind turbines; assessment and health monitoring of offshore platforms; regional and facility-based seismic risk assessment; soil-structure interaction analysis.

Kutay Orakçal serves as Associate Professor and Co-Director of the Structural Eng. Laboratory within the Department of Civil Eng. at Boğazici University. Dr. Orakçal graduated from Middle East Technical University in 1998, and received his MS and PhD degrees from the University of California, Los Angeles. His research interests lay in the field of structural and earthquake eng., with emphasis on response assessment for structural elements and systems subjected to earthquake actions, through laboratory testing, field testing, and analytical modeling. He also serves in seismic code committees on design on reinforced concrete structures and tall buildings.

Erdem Canbay is a professor of civil eng. at the Middle East Technical University, Ankara, Turkey. He received his BS from Istanbul Technical University, and his MS and PhD from Middle East Technical University. He was a post-doctoral research associate at Purdue University between 2001 and 2003. His research interest focuses mainly on reinforced concrete structures, rehabilitation of RC structures against earthquakes, and experimental approaches.

Masoud Motavalli is the Head of the Structural Eng. Research Laboratory at the Swiss Federal Laboratories for Material Science and Technology, EMPA and lecturer at the Swiss Federal Institute of Technology, ETH-Zurich. He is a Professor at the University of Tehran, Iran, Faculty of Civil Eng., as well as Adjunct Professor at the Monash University, Melbourne, Australia. He obtained his Doctor of Eng. at the Swiss Federal Institute of Technology, ETH-Zurich in 1992. His laboratory at EMPA is one of the largest structural eng. laboratories for carrying out full scale structural tests in Europe. His research interests are the application of advanced materials such as multi layered fibre reinforced polymers and shape memory alloys in civil eng. structures, micro and macro mechanical behaviour of these materials, rehabilitation and repair of existing structures with post-tensioned advanced materials. He is a council member of IIFC and ISHMII, Member of the ASCE Committee on Performance Based Design and Evaluation, as well as member of the editorial board of several journals such as Journal of Civil Structural Health Monitoring. He organized or co-organized several successful international conferences, such as CICE2008 in Zurich, SHMII2009 in Zurich, SMAR2011 in Dubai, SMAR2013 in Istanbul and is co-chair of SMAR2015 in Antalya, Turkey. Professor Motavalli is co-author of more than 150 peer reviewed journal and conference papers.

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Reyes Garcia is a Research Associate at the Department of Civil and Structural Eng. of The University of Sheffield (UK). He obtained his BEng (Hons) from the University of Michoacan (Mexico), his MSc from ROSE School (Italy) and University of Grenoble (France), and his PhD from The University of Sheffield (UK). His main research interests are in the fields of structural concrete, FRP reinforcement and earthquake engineering. He has significant experience in the behavior and retrofitting of full-scale reinforced concrete buildings tested on shake tables. He is a member of the *fib* TG 9.3 "FRP Reinforcement for Concrete Structures" and of the EU-funded COST Action TU1207 "Next Generation Guidelines for Composite Reinforcements".

Santiago Pujol is an Associate Professor at Purdue University. He is a member of ACI committees 133, 314, 318R, and 445.

Khalid M. Mosalam obtained his BS and MS from Cairo University. In 1996, he earned his PhD from Cornell University in Structural Eng. In 1997, he joined the faculty of the Department of Civil and Environmental Eng., University of California, Berkeley (UCB) where he is currently a professor of structural eng. and the leader of the Structural Engineering, Mechanics and Materials program. He conducts research on the performance and health monitoring of structural systems of concrete, masonry, and wood subjected to extreme loads. He is active in the areas of assessment and rehabilitation of essential facilities such as bridges and electrical substations. His research approach covers large-scale computations (deterministic and probabilistic) and physical testing including hybrid simulations. He is the recipient of the 2006 ASCE Walter L. Huber Civil Engineering Research Prize with citation: "For advanced computational research integrated with large experiments to solve practical structural engineering problems." Because of his international collaboration for seismic safety and regulations of low cost housing in Morocco, he was awarded the 2013 UCB Chancellor award for Public Services. He is active in the area of building energy efficiency and sustainability.

An Experimental Study on 6-Story R/C Structure with Multi-Story Shear Wall

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In order to study what amount of lateral force and varied axial force are carried by the wall frame in reinforce concrete buildings with multi-story shear wall, the pseudo-dynamic test with 2-span-1-bay-6-story reinforced concrete structure with a multi-story shear wall was conducted. The scale of the specimen was one-third. At first, one hydraulic actuator was connected to each floor but two to the top floor to simulate 6-degree-of-freedom system. It was impossible, however, to control since the stiffness of the continuous shear wall was too high. Therefore, only two floors, 4th and top floors, were loaded to reproduce the first mode of the specimen.

The parameter of the test was the rigidity at the bottom of the continuous shear wall. At first, the bottom of the continuous shear wall was not fixed to reaction floor and the rocking behavior was restrained by the transverse beams. After inputting four different ground motions, the bottom of the continuous shear wall was fixed and inputted four more ground motions.

The test results were discussed with the numerically calculated strengths in terms of the varied axial force borne by the wall frame, lateral force carried by the wall frame, lateral force distribution mode, and the equivalent height of the specimen and the wall frame.

On-Site and Laboratory Tests on Sliding Base Foundations for Reinforced Concrete Buildings

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Lateral loading test on the spread foundation of an existing school building was conducted in April 2010 to identify the lateral stiffness of the foundation. A part of the building was separated through the foundation to the roof level, to which static or impact load was applied horizontally at the base foundation level. The test results were compared with analytical model based on boring investigation into the soil. Another series of static and dynamic loading test on sliding at the base of base foundation were conducted from 2012 to 2013 using component scale model of concrete joint faces. The joint detailed was varied to find simple and economical joint faces with less friction coefficient to reduce higher acceleration of input base motion at extreme earthquake. The objective, plans, testing methods and the detailed test results on the sliding of base foundations are reported at the workshop.

To identify the lateral stiffness of the spread base foundation including the non-linear deformation properties of the soil underneath, dynamic and static loading tests on an existing low-rise building were planned in this study. The impact and static lateral loads were applied at the level of the spread foundation in the existing three-story reinforced concrete school building in Ojiya City, Niigata prefecture. The building was more than 45 years old and was subjected to major earthquake motion during the Niigata-ken Chuetsu earthquake 2004. However, the observed damages were minor, although a very strong motion up to 0.8G was recorded at the K-net Ojiya station, which was adjacent to the building site. Also it has been identified by aftershock observation (Kabeyasawa, 2006) that the intensities of the recorded motions were apparently different between the K-net station and the temporary station at the building base.
The lateral stiffness from the on-site test and the equivalent damping coefficient are compared with theoretical calculation. The elastic stiffness from the test of impact loading approximated to the theoretical stiffness. The secant stiffness to the maximum loads gradually decreased with non-linear maximum response of the ground soil, though the inelastic displacement was not large enough in the test of impact loading. The equivalent damping coefficient from the test was much higher than the theoretical estimate.

It was found from the dynamic and static component tests that the friction coefficients are 0.4 to 0.6 at concrete to concrete joint, around 0.2 to 0.3 at concrete with steel plate, while it could be reduced down to 0.07 to 0.1 at a new joint detail.

Seismic Rehabilitation and Re-Assessment of Existing Underperforming RC Buildings

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The issue of seismic vulnerability assessment and rehabilitation of underperforming existing buildings is a very important and complex problem, especially in seismic-prone countries such as Turkey, Italy and Greece. Current codified procedures for the assessment of such structures include a number of analysis options, ranging from linear response spectrum to more refined pushover analyses, which are not always familiar to the practicing engineer. A vulnerability assessment study, especially if the structure exhibits some peculiar features, such as in-plan- or in-height irregularity, older rebar arrangements and outdated structural detailing, unusual materials, such as low strength concrete and non-corrugated steel rebar, can thus yield very scattered results, depending on the type of analysis and the basic modeling assumptions adopted by the engineer. The same holds true for the design of a retrofitting intervention: a wide range of options is available to the practitioner, but no codified approach can provide prescriptive guidelines that fit any and every case, because an effective retrofitting strategy needs to take into account a number of factors, such as the main structural issues highlighted in the vulnerability analysis, budget constraints, feasibility issues, owner's requirements and a number of other boundary conditions.

In recent years, an extensive research activity has been carried out in order to experimentally investigate the response of existing buildings and to derive some general concepts to guide practitioners tackling the complex issue of seismic retrofitting. In particular, in the framework of the research activity of the ELSA Laboratory of the Joint Research Centre, pseudo-dynamic testing of a real-size plan-wise irregular 3-storey frame structure, both in the as-built and in two retrofitted configurations, was carried out as the core of the research project SPEAR (Seismic PErformance Assessment and Rehabilitation of existing buildings). The experimental activity carried out on the SPEAR structure allowed a one-of-a-kind wealth of data to be collected. In the pre-test phase, a blind vulnerability assessment study was carried out, using different software and analysis options, so that the scatter of the results could be gauged and the effectiveness of the different modelling assumptions in providing a reliable estimate of the experimental response could be assessed by comparison with the test results. Once in the post-test phase, it became clear that a good understanding of the complex features of the response of the specimen was difficult to be obtained, due to the effects of double eccentricities, adding up to poor structural detailing and lack of ductility. Still, it was felt that a kind of easily applicable and extendable lesson should be derived from that complexity, and that a fully performance-oriented interpretation and evaluation of the results could be attempted, in order to provide an effective tool to compare the effectiveness of different possible retrofitting strategies in complex scenarios. In particular, two different retrofitting strategies, a ductility-oriented FRP wrapping intervention and a strength- enhancing and rebalancing RC jacketing intervention were designed, in order to tackle the main structural issues highlighted by the numerical analysis and by the test results, i.e. lack of global and local ductility and remarkable torsional effects negatively affecting the seismic response.

A performance-based assessment exercise was thus carried out, in order to assess the effectiveness of both strategies in an objective way. This included the estimations of the costs of the different damage states, provided by the engineering practice. The probability of attaining each damage state was obtained by combining the experimental skeleton curves with the probabilistic definition of the expected intensities and conclusions were finally drawn on the effectiveness of the retrofitting interventions in terms of reduction of the expected loss during the lifetime of the building.

Role of Large-Scale Testing in Assessing the Performance Enhancement of Structures with FRP Composites

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Fiber–reinforced polymer (FRP) composites provide an important technology to enhance the performance of existing or new structures. For this technology to be widely used, extensive research is needed on the performance of structures incorporating FRP composites. Such research often needs to be undertaken experimentally, and the size of the test specimen is often an important issue. This presentation provides a brief report on two aspects of the author's recent work: (a) testing of large FRP-strengthened concrete columns and beams under static loading to examine the size effect; (b) cyclic lateral loading tests of large-scale hybrid columns with FRP using a large purpose-built testing frame, with the latter being given much more attention.

Following the presentation of some interesting results on the size effect of FRP-strengthened concrete members, the presentation will introduce the large testing frame for cyclic loading tests of columns located at the Structural Engineering Research Laboratory of The Hong Kong Polytechnic University. This testing frame includes a vertical actuator with a capacity of 10,000 kN in compression and 3,000 kN in tension, and a horizontal actuator with a capacity of 1,500 kN in compression and 1,000 kN in tension. An important feature of the testing frame is that the position of the vertical load can move with the column head so that it remains vertical during cyclic lateral loading. The testing frame has a testing space of 3.2 m in width, 2.0 m in depth and 3.5 m in height. The results of two series of cyclic loading tests conducted using this testing frame will be presented. The first series consisted of FRP-confined concrete-filled steel tubular columns with a diameter of 318 mm and a height of 1,625 mm while the second series consisted of hybrid FRP-concrete-steel double-skin tubular columns with a diameter of 300 mm and a height of 1530 mm. These tests provided valuable data for understanding the behavior of these two types of hybrid columns with FRP.

Seismic Retrofitting Masonry-Infilled RC Structures via TRM

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Retrofitting non-seismically reinforced concrete masonry-infilled frames is an issue of worldwide concern. Among the several methods proposed, application of textile-reinforced-mortars (TRM) is one of the most recent approaches: it concurrently enhances the resistance of RC members and of masonry infilling, with very promising results in the cases examined so far (sub-assemblies). The approach has been examined at Structures Laboratory of the University of Patras on nearly full-scale, as-built and retrofitted, three-storey frames, subjected to in-plane cyclic loading. The 2:3 scale as-built frame representing typical structures with non-seismic design and detailing characteristics tested as reference was subjected to a height-wise linear pattern of forces. In this structure the two-wythe masonry infill cracked and detached from the surrounding frame, forming a diagonal compressive strut that led to the failure of one of the ground floor columns at its interface to the joint. The companion frame was retrofitted via TRM jacketing: two and one layers of TRM were applied on the ground-floor masonry and the rest floors, respectively, with their extremities extending over the surrounding columns. Special anchors were developed to ensure force transfer to the top and bottom slab at each floor. The response revealed an increase in lateral stiffness and strength and an appreciable magnification of frame-infill deformation capacity. Owing to the previous application of a TRM jacket over the column ends, columns underwent unscathed the loading history up to ground-floor interstorey drift ratio of 4%, despite the strength increase in the diagonal strut due to the TRM.

Hybrid Simulation of Bridge Pier Uplifting

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A structure can be protected from seismic damage, i.e. be very resilient to earthquakes, if it rocks as a whole with respect to the ground, or its components rock in a stable manner relative to each other as rigid bodies, if possible with supplemental energy dissipation to reduce the displacement response. To examine how rocking can enhance structural resilience of bridges subjected to seismic events, a two-span bridge was designed according to EN1998-2 and experimentally tested via sub-structuring (hybrid simulation). In the design emphasis was placed on the dimensioning of the footing so as rocking may develop, as well as on the torsional stiffness of the deck, in light of the provisions of EN1998-2 for the possibility of deck uplifting at the abutments and forcing the support bearings in tension.

Hybrid simulations were performed on this “seismically resilient bridge” concept being seismically excited in the transverse bridge direction, having the pier monolithically connected to the deck and the footing assumed to rock and uplift. The deck was also allowed to uplift from its supports at the abutments. For comparison the same system was examined with the footing assumed fixed. The pier was physically represented in half-scale and always fixed on the laboratory strong floor, while the deck, the pier foundation (with or without soil compliance accounted for) and the support bearings at the abutments were numerically simulated at full scale through SimCor and Opensees. Two degrees-of-freedom were assumed at the pier top to simulate deck resistance to pier deformation; thus, for applying the computed displacement and rotation at the pier top, two actuators were employed at the stub which representing the region of pier-to-deck connection. Purpose-built software linked the SimCor platform to the laboratory control system – the same software performed scaling transformations, as well as all necessary computations and geometric transformations to obtain actuator command signals and proper force feedback values.

Under 0.15g peak acceleration excitation the pier responded quasi-elastically for both cases tested (with the free-to-uplift pier configuration tested first), although with a lower period in the case of the fixed-base pier. Testing proceeded with the pier considered acting as cantilever subjected to top deformation only, either fixed or allowed to rock at the base. With the input excitation applied with 0.40g peak acceleration level, cracking in the pier with the rocking foundation was minor, while uplifting was noted at several instances during the response. In the fixed-base pier case higher drift ratios were observed compared to those in the free-to-uplift specimen and the specimen reached yielding.

Field Testing of Full Scale Reinforced Concrete Buildings for Seismic Performance Assessment

In this study, static and dynamic tests were carried out on two full scale substandard reinforced concrete buildings (Building-1 and Building-2). The aim of the tests was to investigate the seismic performance and obtain the dynamic characteristics (modal frequencies, mode shapes, damping ratios) of these buildings. Building-1 is an existing building more than 20-years-old, which was demolished partially to obtain the 3-story test structure. Since, in case of Building-1, axial load levels were quite low (10% of the axial load capacity of the column), columns were stronger than beams (strong column-weak beam), and the material characteristics were too heterogeneous, it is found to be necessary to construct a single-span, 3-story second substandard building (Building-2) to represent existing buildings, which do not comply with current seismic design codes, but have consistent material characteristics. Moreover, Building-2 was intentionally constructed with smaller column cross-sections (strong beam-weak column) and higher axial loads (25% of the axial load capacity of the column). The buildings had concrete compressive strength of 10 MPa, and were constructed with plain reinforcing bars. The reinforcement detailing (such as lap splices, stirrup spacing, hooks etc.) of both buildings was also representative of relatively older existing structure stock.

In the quasi-static lateral loading part of the study, both buildings were subjected to lateral displacement cycles exerted by the hydraulic actuators positioned at the lower first and second story slab levels. A 50 cm thick reinforced concrete reaction wall, which allowed the testing of both buildings consecutively in a short period of time, was built for supporting the actuators. The reaction wall and the buildings were resting on a 60 cm thick mat foundation that restrained the rocking behavior. The vertical loads were maintained by utilizing the self-weight of the structures. Observations and measurements made during the tests addressed to different failure modes for each building which had different column axial load levels and column/beam bending capacity ratios. The observed failure mechanisms were also similar to ones observed in existing structures after major earthquakes. In addition to observations on evolution of damage, lateral load-story displacement curves, column and beam rotations were also obtained and compared with the nonlinear structural analysis results.

In the dynamic testing, firstly, modal analyses of the building were performed so that the dynamic characteristics could be estimated. Then, forced and ambient vibration tests were carried out at the site for obtaining the dynamic characteristics of the buildings. The excitations were recorded using piezoelectric accelerometers. Dynamic tests were conducted before and after each quasi-static cyclic loading. The dynamic tests were performed at a set of damage levels, for observing the rate of changes of the dynamic characteristics with the increasing damage. For forced vibration tests, buildings were excited via eccentric mass shaker by applying a sinusoidal forcing in a frequency band of 1 Hz to 15 Hz. According to test results, it was observed that the modal frequencies tend to decrease while damping ratios for the different modes tend to increase with the increasing levels of damage.

Statik: M. Comert, C. Demir, A.O. Ates, E. Tore, O. Ozeren, A. Moshfeghi, S. Khoshkholghi, M. Senturk

Dinamik: C. Goksu, P. Inci, U. Demir, I. Saribas, A. N. Sanver, U. Yazgan

K. Orakcal, A. Ilki

Structural Health Monitoring For Seismic Reliability Estimation

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Structural Health Monitoring (SHM) enables engineers to identify actual dynamic characteristics of structures such as modal frequencies, shapes and damping ratios. System identification may be carried out by processing ambient, wind or earthquake response (mostly acceleration data) in time or frequency domain. It is well-known that dynamic characteristics generated from the Finite Element Model (FEM) and vibration data, even for intact buildings, show remarkable differences. Assumptions made in the FEM are one of the main reasons for those differences. Therefore, obtaining actual dynamic parameters is crucial in FEM updating and consequently estimating more reliable structural responses. In addition, performance of structures during earthquakes can be examined and possible damage intensity and location may be detected.
To examine feasible solutions to such problems mentioned above, three different applications were explained in the following parts. First, identification, FEM updating and seismic reliability estimation of a tall building was explained. Then, consideration of same procedure for a historical building was summarized. Lastly, seismic reliability estimation after damaging events was elaborated.

A twenty-six story, core-wall tall building in Istanbul was instrumented with vibration sensors. Natural frequencies, mode shapes and damping ratios of the structure were determined by enhanced frequency domain decomposition method. FEM of the structure was constructed based on design drawings and then updated using identified modal values. By using the updated FEM, seismic performance assessment of the building for a possible earthquake caused by the North Anatolian Fault was carried out in a probabilistic framework.

A masonry historical building in Istanbul constructed in 1925 was considered. In-situ and laboratory test results for the building material were used in FEM. Ambient vibration tests were also carried out to obtain actual and global dynamic characteristics of the building. Based on identified modal values, FEM was updated. Seismic failure probability was obtained by fitting a log-normal distribution to the maximum base shear demands obtained under different input motions and then calculating the exceedance probability of a threshold value.

A series of earthquake and white noise excitations are imposed to a three-bent reinforced concrete bridge by three-shaking tables, simultaneously. Progressive structural damage is measured and observed, in accordance with increasing intensities of damaging events. Response measurements are obtained by accelerometers located on the deck and the columns of the bridge. FEM for non-updated and updated cases were obtained. Afterwards, damage detection and reliability estimation were carried out for these two cases using fragility curves. It is shown that fragility curves of updated models significantly differ from fragility curves of non-updated models.

Ambient and Forced Vibration Testing of a Reinforced Concrete Building before and after Seismic Strengthening

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The seismic performance of reinforced concrete buildings depends on their lateral stiffness and mass distribution, as well as their lateral load capacity and ductility characteristics. In recent decades, seismic strengthening of existing buildings has been commonly employed for improving their performance under severe earthquake excitation. The results obtained from vibration tests and system identification methods specifically provide valuable information on the influence of seismic strengthening on the lateral stiffness attributes of the building, and help evaluate the effectiveness of the strengthing technique applied, in terms of improving the building's vibration characteristics and seismic performance.

In this study, ambient and forced vibration tests were conducted to evaluate the influence of the seismic strengthening on the vibration characteristics of the six-story reinforced concrete ET-B building, located on the Boğaziçi University Campus in Istanbul, Turkey. Modal vibration characteristics of the building were identified at various stages of strengthening. Ambient vibration tests were conducted on the building before and after its seismic strengthening, whereas forced vibration tests were carried out after strengthening. Results of the tests enabled quantifing the changes, due to strengthening, in the modal characteristics (modal frequencies and mode shapes) of the building, and variation in the modal characteristics of the strenghened building with the intensity of shaking. In addition, simple finite element models of the building were generated, representing its structural configuration before and after seismic strengthening, also considering the impact of the brick-infill partition walls on its stiffness characteristics.

The building was strengthened via jacketing of columns, addition of structural walls, and construction of a mat foundation. During strengthening, partition walls were demolished; and as a result, the first modal frequency of the building decreased by 11%, based on the results of the ambient vibration tests. The ambient vibration tests also demonstrated that the modal frequencies after the seismic retrofitting increased by almost 96%. During the forced vibration tests, it was found that the modal damping values increased with the amplitude of the excitation force.
The experimentally-identified modal vibration parameters of the building were compared with the results of the finite element model generated. The experimental and analytical results were found to be consistent in representing the pronounced influence of the structural walls on the lateral stiffness and thus the vibration characteristics of the building, as well as the relatively minor, yet noticeable influence of the brick-infill partition walls on its vibration characteristics.

Seismic Testing for Risk Assessment of Masonry Buildings

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Risk assessment of masonry structures are conducted following the new design guidelines of the Turkish Earthquake Code (TEC 2007). In that approach a seismic response modification factor of 2 is employed along with linear elastic analysis. Afterwards, masonry wall lateral load capacities are checked considering only sliding shear failure mode. This approach has many deficiencies from assumed material strength to failure modes and is not compatible with the performance based assessment methods of reinforced concrete structures in TEC (2007). In order to propose a new risk assessment methodology, a comprehensive research project was conducted to examine in situ material strength of masonry, to estimate performance of a number of masonry structures with analytical and experimental methods. In this brief, we present our experimental findings on the testing of masonry structural systems.

Forced Vibration Measurements on a One-Family Masonry House and 3-Story Residential Light-Frame Timber Building in Switzerland

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In this study, the results of Forced Vibration Tests (FVT) on two residential buildings in Switzerland will be presented. The first project involved FVT on a masonry house in Monthey, Switzerland, consists of a basement, a ground floor and a first floor. Two hydraulic cylinders with maximum dynamic force of 32 kN each were mounted on the first floor. A force transducer measured the shaker force and the aggregates were operated in displacement control mode. Both single harmonic and band limited random displacement command signals were used for excitation of the building. The building response was measured with accelerometers distributed on the first floor and in the centre of the ground floor and basement. Ambient vibration measurements showed that the first natural frequency was approximately 10 Hz. Based on that, the house was excited by band limited random signals within the frequency range of 5 to 20 Hz with increasing dynamic forces. The goal was to investigate the influence of the excitation intensity on the eigenfrequencies and damping ratios. The tests demonstrated a strong dependency of the eigenfrequencies and damping ratios on the excitation intensity. The reason for that nonlinear behaviour seems to be related to the interaction between structure and soil. An additional test series with sinusoidal shaker forces was performed with the goal to drive the house into resonance and to thereby to force damage. However, due to the very strong system damping, damage could not be generated.

The second project was to investigate the dynamic properties of a recently built 3-story residential building near Zurich, Switzerland with dimensions 14.5 x 24 x 11 m (width, length, height) constructed using OSB-sheathed light-frame timber wall elements and timber-concrete composite slabs. The building was subjected to FVT in three different stages of construction. The experimental campaign consisted of acceleration measurements after forcing the building to vibrations by means of a 2 ton hydraulic shaker with 940 kg of horizontally moving mass. The shaker was positioned on the second floor of the building and rigidly anchored in the slab. It subjected the building in its two main directions to vibrations with frequencies of 0.2 – 14 Hz and amplitudes of +/-0 - +/-125 mm. The experimentally derived dynamic properties were then compared to analytical and numerical calculations using a cantilever beam with three lumped masses and a 3D finite element model. It turned out that with beam-type models it is possible to estimate the fundamental periods with only limited accuracy. The 3D model on the other hand exhibited a much better performance. However, also there the quite big differences between experimental data and numerical model let conclude that the building in reality was much stiffer than expected. One of the main reasons for this discrepancy was identified in the marked contribution of non-structural internal walls to the overall horizontal stiffness of the building. In addition the eigenfrequencies were found to moderately decrease with increasing amplitude whereas modal damping increased markedly with increasing amplitude. The differences of dynamic properties assessed in the three different stages of construction were much smaller than expected. The impact of additional stapling of the OSB sheathing panels to the timber frame of those walls being part of the horizontal bracing system was less pronounced than the impact of adding non-structural internal walls plus door and window frames in stage 3.

Vibration Based Damage Detection of a Scaled Reinforced Concrete Building by FE Model Updating

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The traditional destructive tests in damage detection require high cost, long consuming time, etc. The powerful equipments with advanced technology have motivated the development of global vibration based damage detection methods. These methods base on observation of the changes in the structural dynamic properties and updating finite element models. The existence, location, severity and effect on the structural behavior of the damages can be identified by using these methods. The main idea in these methods is to minimize the differences between analytical and experimental natural frequencies. In this study, an application of damage detection using model updating method was presented on a scaled reinforced concrete (RC) building model. The model was designed to be 1/2 scale of a real building. The measurements on the model were performed by using ten uni-axial seismic accelerometers which were placed to the floor level. The presented damage identification procedure mainly consists of five steps: initial finite element modeling, testing of the undamaged model, finite element model calibration, testing of the damaged model, and damage detection with model updating. The elasticity modulus was selected as variable parameter for model calibration, while the inertia moment of section was selected for model updating. The first three modes were taken into consideration. The possible damaged members were estimated by considering the change ratio in the inertia moment. It was concluded that the finite element model calibration was required for structures to later evaluations such as damage, fatigue, etc. The presented model updating based procedure was very effective and useful for RC structures in the damage identification.

Shake Table Tests on Two Deficient Full-Scale RC Structures Retrofitted Using External Reinforcement

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In the last decade, strong earthquakes in developing countries (Kashmir, 2005; China, 2008; Indonesia, 2009; Haiti, 2010) caused numerous casualties and financial losses due to the collapse of many reinforced concrete (RC) buildings. Many structural failures were attributed to the inadequate behaviour of beam-column joints. The local strengthening of substandard joints is essential to reduce the seismic vulnerability of such deficient buildings. Over the last years, the use of externally bonded Fibre Reinforced Polymers (FRP) has offered engineers a feasible solution for strengthening seismically deficient buildings. Comparatively to traditional strengthening techniques, FRP materials offer high strength to weight ratio, high resistance to corrosion, excellent durability, ease and speed of in-situ application and flexibility to strengthen selectively only those members that are seismically deficient. However, limited research has investigated the effectiveness of FRP at enhancing the seismic behaviour of deficient joints in full-scale RC frames using shaking table tests.

Early work at the University of Sheffield led to the development of a novel patented strengthening technique for RC elements using Post-Tensioned Metal Straps (PTMS). The PTMS technique involves the post-tensioning of external high-strength steel straps around RC members using hydraulically-operated steel strapping tools similar to those utilised in the packaging industry. After post-tensioning, the straps are fastened mechanically using push-type seals to maintain the tensioning force. This provides active confinement to members, thus increasing their ductility and capacity. PTMS has advantages such as ease and speed of application, low material cost, ease of removing/replacing damaged straps, and flexibility to strengthen different types of structural elements. The use of PTMS in developing countries is expected to lead to more cost-effective solutions compared to strengthening methods such as externally bonded FRP reinforcement. Whilst the PTMS technique has been used to retrofit RC columns, further research is necessary to assess its effectiveness at enhancing the structural performance of large-scale structures.

This presentation will show experimental results from two full-scale RC buildings tested on a shake table as part of EU-funded projects ECOLEADER and BANDIT. The main objective of these tests was to study experimentally the performance of existing substandard (non-engineered) RC frame buildings retrofitted using either externally bonded FRP reinforcement (ECOLEADER) or PTMS

(BANDIT). It is shown that both retrofitting solutions were extremely effective at enhancing the seismic performance of the two buildings, thus being suitable to reduce the vulnerability of deficient RC structures as those typically found in Mediterranean and in developing countries.

Lap Splices in Unconfined Boundary Elements- Projecting Results from the Laboratory to the Field

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Because lap splices are believed to limit frame toughness, they are not used near critical sections of frames that are required to resist earthquake demands. Nevertheless, the current building code still allows lap splices at the bases of structural walls, where large inelastic deformations are expected to take place during strong ground motions. In the most critical cases, these splices are not located within confined boundary elements.
Certainly, the tensile strength of lap splices has been studied extensively. Nevertheless, failures of unconfined deformed-bar lap splices observed after recent seismic events in Turkey, Japan, and Chile indicate a need to revisit the topic.

In buildings with structural walls, wall toughness is critical to seismic response. While most structural walls are currently constructed with lap splices at their bases, information on the deformation capacity of such walls is scarce. The work described here was aimed at generating data to help fill that gap.

Seismic Experimental Evaluation of Glass Curtain Wall with Shaking Table based on Floor Capacity Demand Spectrum

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Floor seismic demands of curtain wall (CW) relate to the floor response of the main structure where the corresponding acceleration and deformation demands determine the seismic performance of the CW system. Floor capacity spectrum has the ability to combine the two demands into one acceleration-displacement response spectrum (ADRS) by assuming the CW unit as a single degree of freedom system. The in-plane (IP) load-displacement relationship can be transformed into acceleration-displacement format (capacity curve) which is superposed on the ADRS. The intersection of the two curves is the performance point (PP) of the CW system. Another approach to obtain the PP is through the floor response analysis of the main structure and the pairs of acceleration and displacement demands form the demand PPs. In shaking table tests of the CW system, the two coordinates of the PP can be simulated by applying the IP deformation with a specially-designed rigid steel frame, then exciting the test specimen by the shaking table. PPs can be conveniently reproduced and thus the seismic performance of the CW system is assessed. The applicability and reliability of the novel shaking table testing method is discussed through numerical analysis and real shaking table tests of a glass curtain wall specimens.

The seismic demand parameters including the floor acceleration amplification (FAA) and the interstory drift ratios (IDRs) are acquired though the floor response of a tall building subjected to tri-axial ground motions. The actual FAA factor is larger than most current code provisions, while the IDR factor is close to some code provisions. Mean floor acceleration spectra compatible components of artificial floor motions are generated for dynamic excitation of the CW specimens on the shaking table. Drift demand of the CWS is simulated by imposing IP deformations and the floor acceleration demand is reproduced by inputting series of generated artificial floor motions whose peak accelerations are compatible with the FAA factors. Two representative glass CW specimens are tested on the shaking table. The frequency of the tested CWs varied during testing but there was no visible damage in the glass panels. The observed maximum strain response was smaller than the design value. It is found that the component acceleration amplification (CAA) factor is 3.35, which is larger than the code provision. An improved equivalent inertial force calculation based on equilibrium requirements is proposed to show the seismic safety of the CW systems in tall buildings.