

# **EARTHQUAKE RESISTANCE OF STRUCTURES AND DYNAMIC RESPONSE USING LARGE FACILITIES EXPERIMENTS**

Miloš Drdácý<sup>1</sup> and Stanislav Pospíšil

*<sup>a</sup>Institute of Theoretical and Applied Mechanics, Czech Academy of Sciences,  
Prague, Czech Republic,  
[drdacky@itam.cas.cz](mailto:drdacky@itam.cas.cz), [pospasil@itam.cas.cz](mailto:pospasil@itam.cas.cz)*

## **Abstract**

The presented article treats some of the activity of the Institute of Theoretical and Applied Mechanics of Czech Academy of Sciences (ITAM). It focuses on the experimental part of the research that has a broad field of application in the industry and/or that has been dealt within international projects funded by the European commission. The use of European and institutional facilities simulating the earthquake is presented as well as the methods of the structural assessment using dynamic response of structures. Besides the experimental devices and methods used at the ITAM for assessment of vulnerability of structures to dynamic load are briefly mentioned.

## **INTRODUCTION**

The research in the field of earthquake engineering and related questions of structural vulnerability is nowadays not located in the countries with strong earthquake prone areas only but it has rather growing international dissemination. One of the reasons is the fact, that the so-called technical seismicity has to be regarded in the design of new buildings as well as in the assessment of the real structures. There exist many examples of traffic induced dynamic loading in European historical centers of cities that has damaging impact on the value of cultural heritage. This research today is based on the profound experimental techniques, usage of experimental facilities hand in hand with the theoretical research and development of the new methodology. Besides the earthquake research the use of large experimental facilities has also the prospect of testing the structural integrity dynamic loading either on the prototypes or their scaled models.

It is the task of theoretical and applied mechanics to eliminate the effects of seismic and dynamic load or at least limit them, because they exercise unfavourable influence not only on long-term safety of structures and the functional reliability of technological equipment, but also and primarily on the feeling of safety and comfort of the population. This applies both to the newly built and the existing, possibly historically valuable buildings in the proximity of new transport routes or other sources of noise and vibrations.

Institute of Theoretical and Applied Mechanics has been involved in many international projects dealing with problems of structural integrity, vulnerability, protection of architectural heritage and seismic resistance of structures. Due to limited extend of the paper only some of them are briefly described in following separated sections.

## **DAMAGE DETECTION OF CONCRETE STRUCTURES**

Elaboration of the methods of identification and damage detection by means of a dynamic test is one of the main expertise activities of ITAM. It consists in the determination of natural frequencies and vibration modes and a comparison of the results obtained at various stages of damage using modal analysis. The methods are tested by laboratory experiments on relatively simple structures like R.C. plates and panels of the type envisaged for the construction of railway lines as well as the tests of actual structures. Although the works concerned R.C. structures, satisfactory accuracy in the location of imperfections has been attained by the modification of known MAC and COMAC methods and particularly by the original CAMOSUC method (see Pirner et al. 2003). Particular attention is afforded to the damage produced by long-term traffic, i.e. the effect of material fatigue due to repeated loading at the rate of millions of cycles.

Shaking table experiments proved to be an efficient tool in modeling dynamic response of various structures. The experts from ITAM have been involved in the research focused on damage detection on RC frames. A reinforced concrete frame 3x3x3.5m weighting about 12.2 tons with a slab in the upper part has been tested using Multi Axial Shaking Table for Earthquake Reproduction (Giese et al



1999). The eccentricity has been assured by different stiffness of the columns and by the placement of additional eccentrical mass at the top of the frame. The structure has been subjected to kinematic excitations with increasing level of intensity from PGA (Peak Ground Acceleration) 0.025g to 0.63g. Following each shaking the structure has been inspected for cracks and subjected to modal testing. Resulting modal parameters have been obtained by low-level sweep sine harmonic excitation with increasing and decreasing frequency as well as with white noise random kinematic excitations and sine test with constant frequency. The results are summarized in the Pospisil et al 1998.

Fig. 1: A reinforced concrete frame subjected to kinematic excitations with increasing level of earthquake intensity.

## **RESPONSE OF STRUCTURES EXCITED BY WIND**

Dynamics of slender structures, primarily masts and towers, extension of their service life, their long-term reliability is another activity that is covered by researchers from ITAM. With reference to

the increasing requirements imposed on broadcasting technology and the reduction of their wind-induced vibrations, measurements of the response, development and application of vibration absorbers is of need. The last type of these appliances is the spherical vibration absorber developed in recent years in co-operation with industry company, which was applied successfully to two TV towers, as shown in article (Fischer and Pirner, 2001).

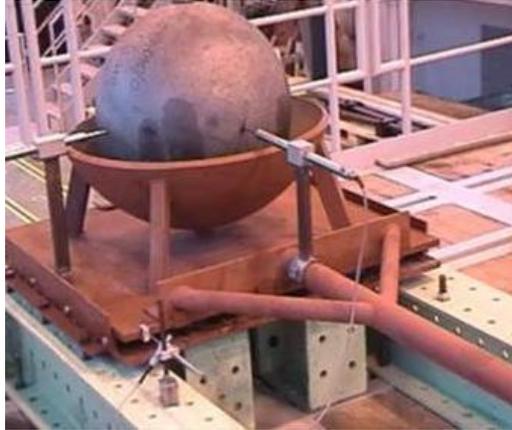


Fig. 2: Ball vibration absorber during the small shaking table experiments

The Institute of Theoretical and Applied Mechanics has a deep experience with aerodynamic tunnel testing of structures susceptible to the aeroelastic instabilities, see for example (Pospisil and Naprstek, 2003). A close cooperation with the Aeronautical Institute of Prague allows carrying out measurements of the influence of wind on civil engineering structures and the environment. A mixed theoretical-experimental research is performed which can help predicting instability onset and influence of the turbulence. The goal of the uniquely designed experiment lies primarily in the observation of the influence of the flow upon response of the structure, possible onset of instability of particular type, stabilization of motion in the postcritical stage, difference between various cross sections and spatial and temporal pressure distribution over the structure in the wind tunnel. Integral load and pressures as well as fluctuating loads are measured. The experiments are partially supported by EU grants within COST action C14.

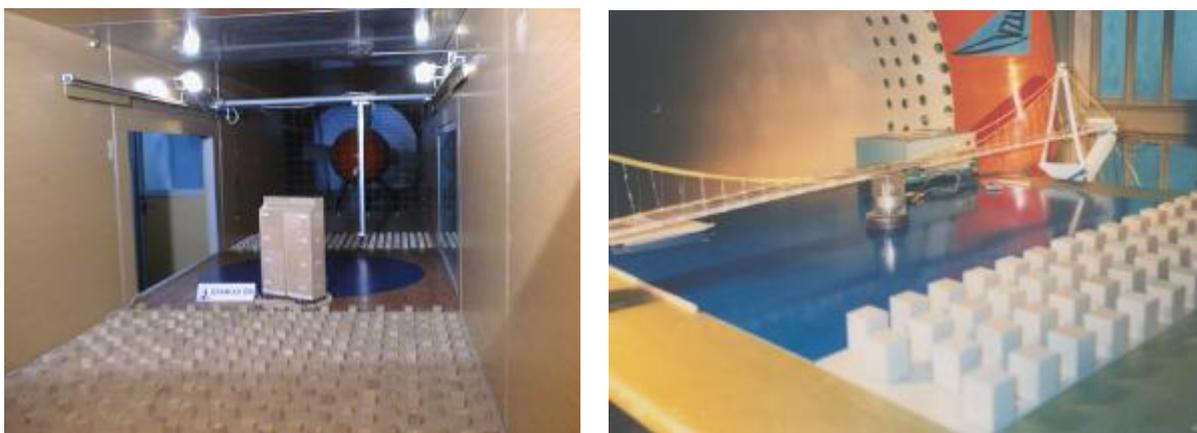


Fig. 3: Use of Boundary Layer wind tunnel for examining the resistance of structural models (tall buildings, footbridges) to the wind load and against aeroelastic effects.

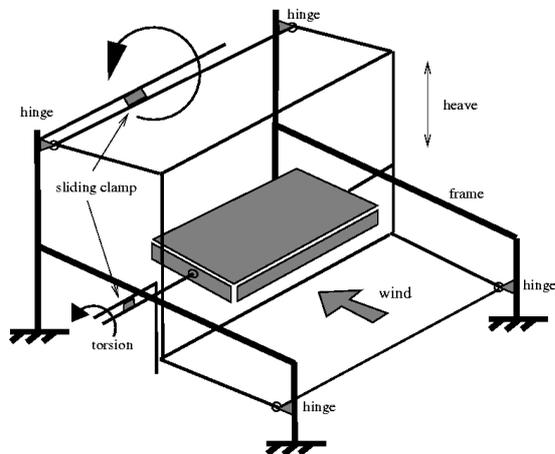


Fig. 4: Dynamic rig with a section model. An original design different from conventional ones (see Hjort Jansen 1996) allows tuning of the frequency of the natural modes independently of each other. The heave motion is assured by a kinematical mechanism hinged at the stiff clamped frame. Vertical beams connect two vertical lever arms at the top and heel of the frame so that motion of the model axis is vertically linear. Rotation of the model is independent as the model is posed on the roller bearing. The frequencies are adjusted by way of sliding clamps that allow setting up the length of torsion springs.

### SHAKING-TABLE INVESTIGATION OF HYDRODYNAMIC PRESSURES IN DAMS

This project has been proposed by a cooperative team from ITAM and EERCE Bristol, based on the work of Mir and Taylor, 1996). Some existing concrete gravity dams initially considered safe are now judged unsafe based on up-to-date specifications. Assuming complete bonding in horizontal joints generally performed the design of concrete gravity dams. However, for detailed safety evaluation of an existing dam, it is necessary to characterize properly the joints, evaluate the possibility of relative motions and consequently evaluate the pore pressure in the joints. A logical location of one of the important horizontal or nearly horizontal joints is the interface between the dam body and the foundation rock. Possibility of sliding in this interface has to be evaluated during safety analysis of a low to medium height concrete gravity dam. There is no reported evidence of excessive sliding of any actual concrete gravity dam subjected to severe shaking. It is therefore desirable to conduct shake table tests of a dam model to verify the predictions and to conduct the numerical simulation of dynamic pressures in the joint. A particular model of a concrete gravity dam has been tested on the shaking table at EERC University of Bristol to investigate especially the hydrodynamic pressures that develop in pre-formed horizontal cracks at the dam base.

Concrete dam model had been created with the geometry according to the figure 1. It was a 1.65m tall and 0.5m wide block with approximate mass 1200-kg. The upstream face is vertical whereas the downstream one has a slope of 1:0.7. To the bottom of the dam a steel plate had been attached. The frictional interface between the plate and the table surface modeled the resistance of a dam monolith against the ground. Afterwards, the dam had been placed into a specially designed tank that retained a relatively small reservoir of water. A schematic sketch can be seen also on the figure 5 below.

There were three major aims formulated in the experiment and successfully measured: To investigate whether significant hydrodynamic pressures build up in the short time the joint is subjected to an earthquake.

- To investigate whether any increase in uplift pressure affect stability or sliding resistance of the dam.
- To acquire data to validate the discrete element method (UDEC) for numerical modeling of the hydrodynamic pressures in a preformed cracks during the motion.

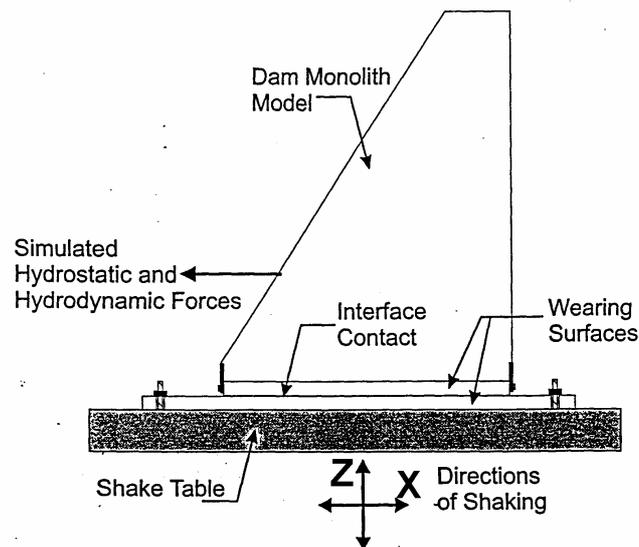


Fig. 5: Schematic sketch of the dam arrangement. X direction: horizontal. Z direction: vertical

## SEISMIC PERFORMANCE OF LAMINATED TIMBER FRAMES WITH FIBER REINFORCED JOINTS



A project sponsored by the EU action ECOLEADER focused on the seismic resistance of timber and hybrid structures has been dealt with in 2002. (See Kasal et. al. 2004). Wood structures demonstrate large energy dissipation capacity due to increased equivalent or total structural damping. This total structural damping is due to the mechanical connectors that exhibit hysteretic behavior under cyclic load. Well-designed connections can undergo large number of cycles without losing design capacity (the ultimate capacity will decrease, however, due to the strength degradation). The stiffness degradation of connections takes place even at low deformation levels (meaning rotations) and causes decrease in the natural of the system. Such decrease is associated with increased total damping. Even strong shaking at levels that can be inadmissible for other buildings such as reinforced concrete or steel frames could not cause the collapse of the

investigated structures. The frame and its 1:4 replica with elements from densified, fiber-reinforced wood is less susceptible to the drop of the structural stiffness than the one with the undesified material. The concept of using high-density reinforced material in connection regions of glue-laminated timber frames can be used in the design of the most exposed structural elements of structures in the earthquake prone areas.

Two-story glue-laminated timber (photo above) frames were subjected to series of dynamic experiments that included sinusoidal sweeps in one direction, arbitrary signals simulation earthquake loads in two directions and harmonic free vibration at fundamental frequency. The frames were made of laminated timber and two experimental frames were manufactured and tested: one control with horizontal laminations and no reinforcement at joint areas and new frame design with densified material in joint area that was further reinforced by glass-fiber composite material. Series of preliminary shake-table tests on scaled models, scaled and full-size beam-to-column connections were performed to obtain connection characteristics needed for subsequent analytical modeling.

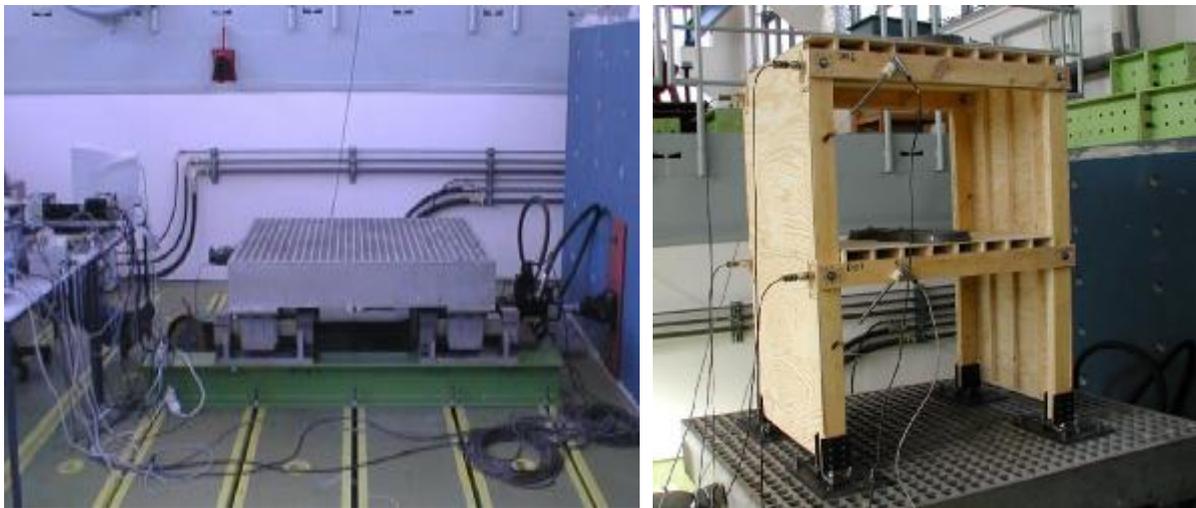


Fig. 6: The shaking table of the Laboratory of Experimental Dynamics. Maximal load of a specimen can be theoretically 1.5t. The table can kinematically excite relatively large-scale models of real structures or their parts and physically simulate an earthquake. Small timber frame (right) was reinforced by yarn composite layers and tested in ITAM.

## **STUDY OF SEISMIC RESISTANCE OF STEEL FRAMES**

During strong earthquakes, excessively large deformation can occur in the joints, which exceeds the elastic range. There is theoretical and experimental evidence, that the number of cycles for the plastification can be more then several tens.

The experiments showed very high sensitivity of welded joints and areas with notches to the low cyclic fatigue due to high concentration of stresses. It has been also shown that it is appropriate to include this fact into the static analysis and design calculation. The maximum deformation of the elastic structure cyclically loaded is lower than maximum deflection elastic structure where no changes of initial stiffness occur; see for details work of Urushadze 2001.



Fig. 7. Experiments on seismic resistance of steel frames taking into account the ductility (Resulted in a recommendation for NAD Eurocode 8). The reaction wall of Laboratory of Experimental Dynamics, ITAM was in use. By courtesy of Dr. Shota Urushadze – Central Laboratory for Experimental Mechanics.

## **MASONRY WALLS STRENGTHENED AGAINST SEISMIC EFFECTS**

The recent heavy earthquakes in Central Italy and Turkey have increased interest in the methods of strengthening and reinforcement of masonry buildings, namely historic ones, by means of an exterior composite reinforcement. There is variety of different techniques used to strengthen and reinforce the masonry buildings: e.g. yarn composite strips glued onto the surface or geo-nets mechanically fastened by dowels to the masonry and rendered. Both methods are applicable for preventive strengthening of masonry in regions of higher seismic risks as well as for general remedial works on masonry damaged by cracks. Both methods may be used for cultural heritage objects.

There has been prepared a large experimental programme in order to study the behavior of masonry panels – reinforced as well as plain walls – subjected to combination of vertical and cyclic horizontal loading (Drdacky 2001, Avramidou et al. 1999). This task has been solved in co-operation between Florence University of Technology (Universita degli Studi di Firenze) and the Institute of Theoretical and Applied Mechanics (ITAM) of the Academy of Sciences of the Czech Republic under sponsorship of two Italian producers of composite materials – SEAL SpA Legnano (Fiber reinforced Composite strips with polymer matrix) and TENAX (Geo-nets). The paper summarizes substantial data on completed experiments.

The carried out tests brought about several important results. First, it has been proven that exterior composite strips laminated on the wall surface increase load carrying capacity of those walls at horizontal (shear) loading. Nevertheless, the increase is not very important, in average only 25%. Approximately same improvement can be achieved using geo-nets, of course, here at much lower cost. The low effectiveness causes also a very low dependence of strengthening on a type of fiber fabric used for construction of the composite strip. The Table 2 shows this dependence very well.

Damaged masonry can be retrofitted by means of composite strips laminate on its surface, which improves the resistance of such walls in such a way that their capacity can overcome strength of plain undamaged walls. The strips do not influence deformability of sound walls; the damaged walls after remedial works have lower modulus than non-reinforced and sound walls. The vertical pre-stress has a



Fig. 8: Testing walls strengthened with FRP composite strips (examples before and after failure).

very substantial influence on wall behavior and damage patterns at shear loading. Higher compression pre-stress, (in a level necessary to prevent overturning), prevents also the generating of significant diagonal shear cracks and supports the occurrence of a set of rather vertical cracks located in the diagonal shear band.

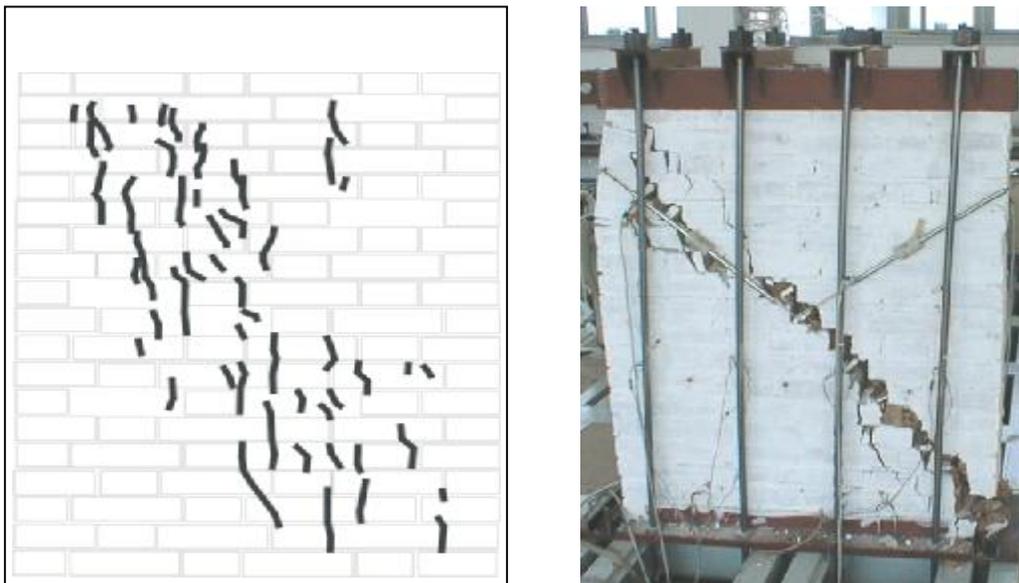


Fig. 9: Left - Crack pattern of walls strengthened using polymer grids. Right – A typical shear crack in a plain wall after collapse under a shock horizontal load combined with unevenly distributed vertical stress.

Because of the high cost of composite strips, this method is economically less effective. A better situation might occur when strengthening natural stone masonry; nevertheless, the low planarity of such masonry decreases the effectiveness again. In both cases, the main disadvantage of surface composite strips is seen in their low fire resistance and a necessity to protect them in this respect when used on dwelling or civil buildings. Geo-nets have a better ratio of strength to the strength of brick and, therefore, their application is more optimal. Taking into account their lower cost and lower workability at application as well as their effect very near to the composite strips, we may recommend their use in favor to composite strips.

## CONCLUSIONS

The article presented some of important research activities focused on the earthquake engineering and structural dynamics carried out at the Institute of Theoretical and Applied Mechanics (ITAM) in cooperation with European research facilities or/and with the industry institutes. We briefly introduced short introduction to the particular topics with main achievements.

The Institute ([www.itam.cas.cz](http://www.itam.cas.cz)) carries out theoretical and experimental research in the field of solid phase mechanics, oriented particularly to building constructions. Its research is focused especially on the dynamics of constructions (stochastic dynamics, aerodynamics, aeroelasticity), nonlinear mechanics, mechanics of classical and nonclassical materials, mechanics of materials failure, and mechanics of soils, on the analysis of properties of constructions, their elements and their reliability. Research is also aimed at the development of new methods of assessment of special-purpose constructions and at problems connected with the protection of historical buildings and settlements.

## ACKNOWLEDGEMENTS

The authors acknowledge ARCCHIP European Centre of Excellence (Advanced Research Centre for Cultural Heritage Interdisciplinary Projects) 5<sup>th</sup> RF Programme INCO “Centre of Excellence ARCCHIP” project ICA1-CT-2000-70013. Also grants of the Czech Grant Agency 103/97/S051, 103/01/0708 and No. 103/01/P078 are gratefully acknowledged. The authors further express thanks to support of Italian companies SEAL SpA and TENAX and also to support by European Community: ECOEST2 ERB FMG ECT 950048, TMR Program, Action 2, Access to large scale facilities, ECOLEADER 2001, Method Statement for Shaking-Table Investigation of Hydrodynamic Pressures Dams, Bristol, GB, ECOLEADER 2002, HPRI-199-CT-00046, Seismic performance of laminated timber frames, ENEL, Bergamo, Italy. The help of Paul Stephan Holzleimbau in Gaildorf (Germany) has been very much welcomed and the support of the European COST project, Action C14 is gratefully acknowledged.

## REFERENCES

- Avramidou, N., Drdácý, M.F., Procházka, P.P., (1999), Strengthening against damage of brick walls by yarn composites, *Proceedings of the 6<sup>th</sup> Int. Conf. On „Inspection, Appraisal, Repairs and Maintenance of Buildings and Structures“*, pp. 51-58, Melbourne, December 1999.
- Drdácý, M., Lesák, J., (2001), Tests of brick masonry walls strengthened with polymer grids and subjected to combination of compression and cyclic shear, *Research report ÚTAM AV ČR - CD, ÚTAM Praha*, August 2001.
- Fischer, O. Pirner, M., (2001), The ball absorber - a new tool for passive energy dissipation of

- vibrations of high buildings., In: *Proc. 7th Int. seminar on seismic isolation, passive energy dissipation and active control of vibrations of structures*, Assisi, 2-5 Oct. 2001. - A. Martelli, ANIDIS-GLIS - Italian national association for seismic engineering - Working group for seismicity
- Hjort-Hansen E., (1992) "Aerodynamics of large bridges", In A. Larsen (ed.), *Proc. of International Conference on Bridge Aerodynamics*, Balkema, Rotterdam, 1992.
- Giese H., A. Kayser and L. Jedenat. (1999), Dynamic identification of an r/c frame in different states of damage, In J. Naprstek and L. Fryba (eds) *Proceedings 4th Int. Conf. of the European Association for Structural Dynamics*, Prague, 7-10 June 1999: EASD, Prague: Balkema
- Kasal B., Pospíšil S., Jírovský I., Heiduschke A., Drdácý M., Haller P., (2004), "Seismic performance of laminated timber frames with fiber reinforced joints". *Accepted for publications in Journal Earthquake Engineering and Structural Dynamics*. Wiley. 2004
- Kasal B, Heiduschke A, Haller P. Fiber-reinforced beam-to-column connections for seismic applications. In *CIB W16 committee meeting*. Kyoto. Japan. 2002
- Mir, R.A. and Taylor, C.A. (1996), "An Investigation into Base Sliding Response of Rigid Concrete Gravity Dams to Dynamic Loading.", *Journal of Earthquake Engineering and Structural Dynamics*, Vol. 25, pp. 79-98, 1996
- Pirner, M., Fryba, L., Urushadze, S. (2003), Identification of imperfections of building structures by dynamic response, In: *Computational Methods and Experimental Measurements 11th* (C. A. Brebbia, G. M. Carlomagno, P. Anagnostopoulos eds.). University of Thessaloniki - Wessex Institute of Technology, WIT Press, Greece, 2003, pp. 333-342.
- Pospíšil S, Kayser A, Giese H, Zembaty Z, Kowalski M, Urushadze S. (1998), Dynamic behavior of crack induced changes in modal parameters of a reinforced concrete frame. In *Proceedings Engineering Mechanics '98, Svatka, Czech republic, 1998*. Volume 3.
- Pospíšil S., Náprstek, J., (2003), Aeroelastic stability of a beam with rectangular cross-section. In: *Proc. of 11th World Conference on Wind Engineering*, (C. Letchford and K. Mehta eds). Lubbock, Texas, USA, pp. 2501-2510
- Urushadze S. (2001), Experimental study of influence of repeated plastic deformation on seismic resistance os steel frame, Phd thesis, ITAM