13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2157

THE CONTRIBUTION TO THE MITIGATION OF TORSION IN SEISMIC RESPONSE

Emília JUHÁSOVÁ[1], Marián VRABEC[2], Martin JUHÁS[3], Vladimír SVRČEK[4]

SUMMARY

The paper deals with the response analysis of those asymmetrical structures that due to different reasons are more vulnerable under the adverse earthquake excitation. The works concentrated on the possible use of vibration control technique taking into account the latest progress in active, hybrid and semi-active vibration control devices. Necessary verifications of their reliability and safety interfere with reasonable initial and service costs. The representative control device was the subject of seismic tests while using variable seismic input and different structure composition. The aim of control was to decrease those vibration components that could substantially influence the seismic failure risk of a respective structure. The series of shaking table tests proved essential improvement of the seismic response in comparison with the original structure response. The advantages of the used methodology appeared in the mitigation of both torsion and translate seismic response components.

INTRODUCTION

Any structure shall be designed such that deterioration over its design working life does not impair the performance of the structure below that intended. The customer, national authority or the designer can decide for higher design working life including necessary changes in respective safety factors and other parameters dependent on design working life. Tools applicable for such purposes belong to family of material and structure measures or special response reduction systems.

In practice there are built also structures with asymmetrical disposition of vertical load-carrying elements. A frequently used system for supporting a structure is a structure with a frame which is reinforced against the effects of horizontal loading by an asymmetrical rigid core, asymmetrically placed shear walls or

[1] Institute of Construction and Architecture, Slovak Academy of Sciences, Bratislava, SLOVAKIA, juhasova@savba.sk
[2] Institute of Construction and Architecture, Slovak Academy of Sciences, Bratislava, SLOVAKIA, marian.vrabec@savba.sk
[3] Department of Automation and Control, Mechanical Engineering Faculty, Slovak University of Technology, Bratislava, SLOVAKIA, juhas@vm.stuba.sk
[4] Department of Automation and Control, Mechanical Engineering Faculty, Slovak University of Technology, Bratislava, SLOVAKIA, svrcek@kam.vm.stuba.sk

different systems of bracing. The selection of the system is often affected by architectural and/or user's requirements. Thus the selection of the system from the point of view of the transmission of the horizontal load is not always optimal. Architects' requirements often prefer e.g. a core support system to a system with peripheral shear walls, although the advantages of the latter are well known to structural engineers, especially with respect to the static horizontal load. Even larger disproportion appears in the case of dynamic horizontal load.

In calculation models, usually the mass of the floor and adjoining vertical elements is considered to be concentrated in the centre of mass M_i. The stiffness centre of the floor is defined as a point through which passes the resultant of the outer horizontal load, which only causes transverse horizontal displacement of ceiling slabs, without rotating them about the vertical axis. The position of the stiffness centre is denoted R_i. If the stiffness centre coincides with the mass centre, then the response of the structure may be solved for both $x - y$ horizontal and for rotation directions separately. It can be proved that for these systems the disposition in plan exists that corresponds to equality of lateral and torsional natural frequencies. However, if the system is asymmetrical, only such dispositions can be found that correspond to limit proximities of these natural frequencies, Juhásová [1]. This knowledge can be utilised when the conception structural control is introduced for mitigation of adverse seismic response.

RESPONSE REDUCTION SYSTEMS AND CONTROL

The development in dynamic response reduction systems is interconnected with the theory, software and hardware of control systems used as optional technology for the increase of total structural resistance capacity. The control algorithms that were developed during the last years suggest more or less convenient options applicable for the control of the dynamic response of the civil engineering structures, e.g. Benchoubane [2], Juhás [3], Loh et al. [4], Molina et al. [5]. These algorithms were verified either by numerical simulations and parametric studies or directly by intended experiments on models or on actual structures.

Special situation appears when the controlled structure has significant asymmetrical features caused by structural system and distribution of masses. The asymmetrical structural system brings the seismic response into remarkable non-uniform distribution of strains and stresses with the unpleasant contribution of shear in torsion. They are usually much higher than respective values of static response. Strength in shear is lower than strength in tension or bending. If the technological reason does not allow symmetrical structure, the question arises how to mitigate the adverse stresses in seismic response. The asymmetry in plan causes a combined dynamic response in which originally independent lateral and torsion natural modes pass into combined lateral-torsion natural modes with the respective increase of bending-torsion stresses in edge vertical elements. Decrease of rotation vibration components is an important issue in ultimate states of deformations and stresses. Therefore, objectives of a presented research were focused on the ability of the control in view of torsion seismic response reduction and appropriate minimization of translate motions.

Several control algorithms were included into numerical parametric case studies to verify their stability, feasibility and robustness under conditions of seismic input with variable properties in time and frequency regions. In the first case – called **ASI yaw** control through kinematic torsion input was generated on the basis of the knowledge of natural frequencies and modes of vibration. Taking into account the adverse effects of those modes with remarkable torsion contribution the primary interest was to suppress these frequency components in the control input with necessary filtering. In the second case – called **TVC yaw** control, the control kinematic torsion input was generated like the simulation with the imposed condition of a minimum torsion vibration in the first storey of the frame. In case of brace control, the **f2** force control was based on minimization of the first storey slab centre velocity that covers both translate and rotation response. The **df** approach applied integral of force feedback for displacement brace control.

An appropriately chosen prototype and model of a structure can serve for both analytical and experimental studies. The analysis followed the seismic response of a frame with the brace; the case of the braced structure submitted to a torsion control at the base and the case when stiff brace is replaced by controlled "intelligent" brace. The same idea concerns the experimental research and verification tests that were carried out using 6DOF MASTER shaking table and second independent hydraulic system in Dynamic Laboratory of ENEL.HYDRO - ISMES Seriate by teams from ICA SAS and FME SUT, Bergamo and Franchioni [6].

COMPOSITION OF INVESTIGATED MODELS

The model was chosen as a two storeys steel frame, one bay, with asymmetrical brace situated in the first storey. The seismic response of the basic asymmetrical system depends on the seismic input properties in relation to brace stiffness. Consequently, optimum brace dimensions exist for any defined earthquake. The stiffness of brace influences dynamic properties of the model. Any dynamic response increases or decreases in dependence on brace stiffness and spectral properties of the input. The intended improvement of the response can be reached either through yaw control at the base or through "intelligent" brace.

As far as the atypical test composition needed the use of two independent laboratory hydraulic systems, the supplementary jack tests were carried out before the use of “intelligent brace” control, Juhásová et al. [7]. The sources of outside excitation were either impacts or external seismic steady vibration. Figure 1 shows the jack test composition and the results obtained. The control efficiency should be thus estimated on the bases of transition from uncontrolled into controlled stage.

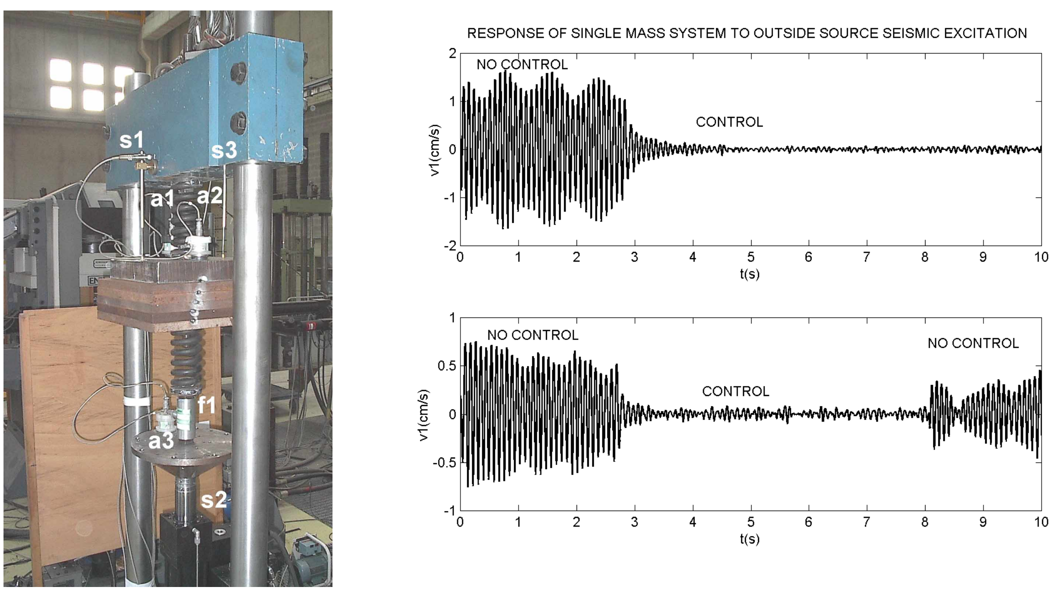

Figure 1. The jack test composition and the effect of control in case of external steady excitation

Calculation modifications of frame model followed the changes in the model structural properties, changes in seismic input and changes in intended control procedure. In investigated frequency range the dynamic response is affected by two natural modes in *x* direction and four coupled lateral-torsion modes in y-θ directions. Experimental frequencies were determined from sequential impact tests by impact I1 up to I6 and from sweep sine tests, see Table 1. Positions of sensors and impact points are given in Figure 2.

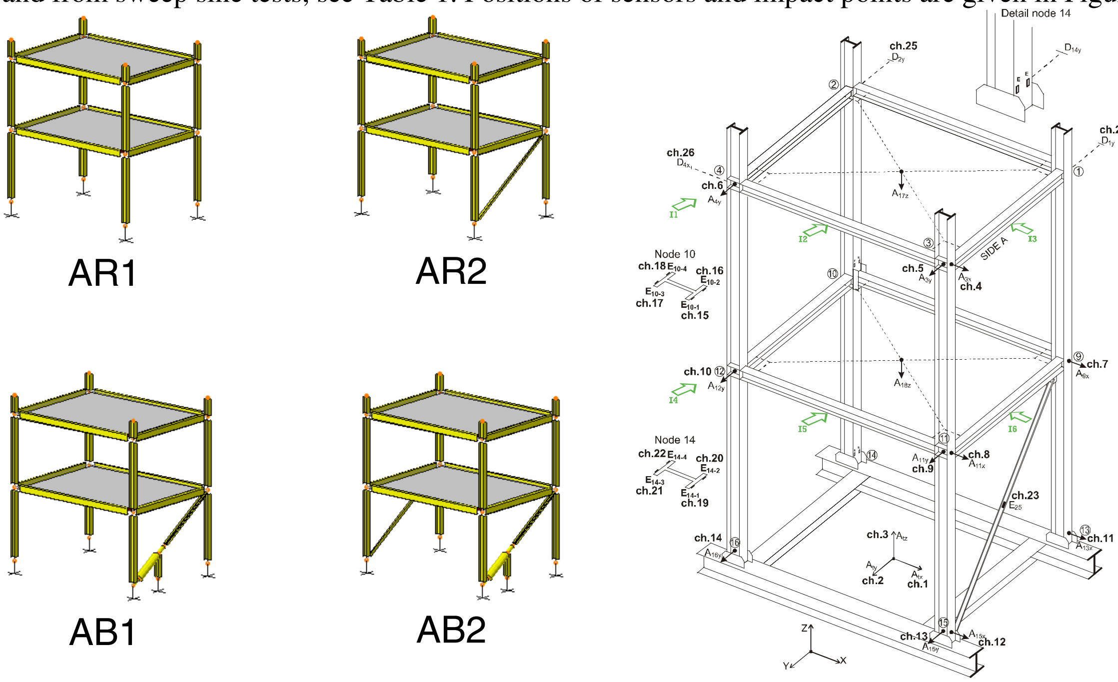

Figure 2. Used tested frame model compositions, impact points and instrumentation

Table 1. Calculated and measured natural frequencies

Direction	$(y\text{-}\theta)_1$	$(x)_1$	$(\theta\text{-}y)_1$	$(y\text{-}\theta)_2$	$(x)_2$	$(\theta\text{-}y)_2$
Model I – $f(j)$ (Hz)	4.33	5.42	6.39	12.41	16.81	23.27
Model II – $f(j)$ (Hz)	4.94	5.11	7.42	14.01	16.88	26.88
Model III – $f(j)$ (Hz)	4.21	5.28	6.23	12.40	16.88	24.72
Exp – impact I1,I2,I4,I5 *	4.14		7.74	13.18		26.64
Exp – impact I3,I6 *		4.52			16.59	
Exp – sweep x - $f(j)$ (Hz) *		4.33			16.59	
Exp – sweep y - $f(j)$ (Hz) *	3.96		7.74	13.18		27.19
Exp – impact I1,I2 **	4.2		7.6	14.2		24.8
Exp – impact I3,I6 **		4.45			16.5	
Exp – impact I1,I2 ***	5.4		9.1	12.45		28.95
Exp – impact I3,I6 ***		4.45			16.35	

NOTE: * - frame with stiff brace; ** - frame with blocked intelligent brace; *** - frame with stiff and blocked intelligent braces.

The laboratory tests of seismic response consisted from following parts:

– basic seismic tests of model with stiff brace, earthquake input in y-direction, no control;
– seismic tests of model with stiff brace, earthquake input in y-direction, control via *yaw* table input using **ASI** and **TVC** algorithm, respectively;
– seismic tests of model with "intelligent brace", earthquake input in y-direction, control of brace force through displacement/force **df** mode and force **f2** mode, respectively;
– seismic tests of symmetric model without any brace, earthquake input in y-direction;
– seismic tests of model with stiff brace on one side and :intelligent brace on the other side, earthquake input in y-direction, control of intelligent brace force through displacement/force **df** mode and force **f2** mode, respectively.

The view of the model during shaking table tests is presented in Figure 3.

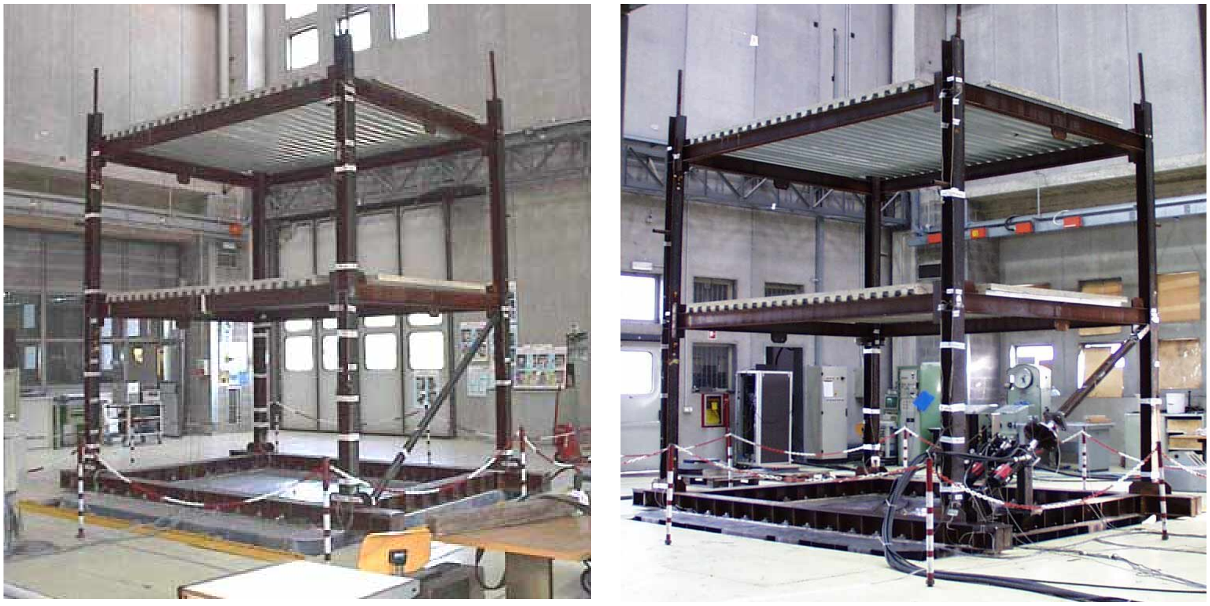

Figure 3. General view of tested frame model, left – with stiff brace, right – with the brace control

ANALYTICAL STUDIES

Considering one mass system with the coordinates passing through the centre of mass, then the free vibration is described by

$$
\begin{aligned}
&m_1\ddot{u}_1(t)+K_{x1}(u_1(t)+e_{y1}\theta_1(t))=0,\\
&m_1\ddot{v}_1(t)+K_{y1}(v_1(t)-e_{x1}\theta_1(t))=0,\\
&I_1\ddot{\theta}_1(t)+K_{\theta 1}\theta_1(t)+K_{x1}e_{y1}u_1(t)-K_{y1}e_{x1}v_1(t)=0.
\end{aligned}
\tag{1}
$$

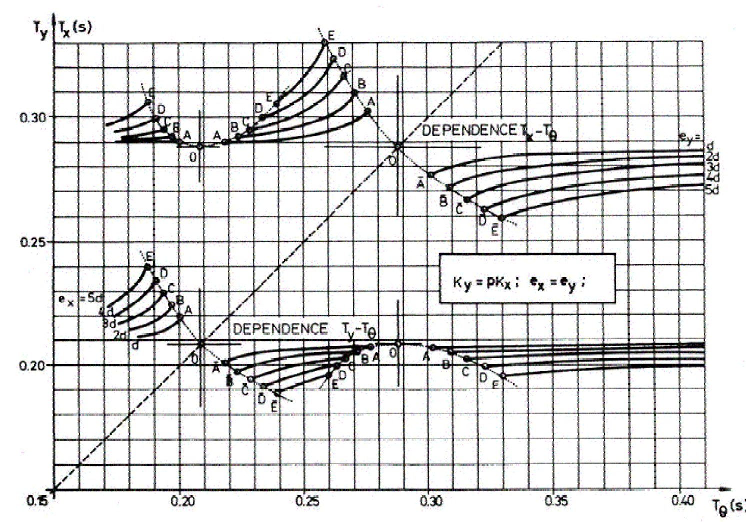

Figure 4. Relation between torsion and translate natural periods at different torsion stiffness

The effects of altering the disposition of vertical elements, i.e. the changes of the torsion stiffness affect the relationship of translate and torsional natural frequencies *f* (or periods *T*). The extreme arrangement, when the translate and torsional natural frequencies are closest to each other, is shown in Figure 4 by dotted line. This scheme indicates the possible increase of rotation response component. For the response of the two storey frame structure to the seismic input, there is:

$$
\begin{aligned}
& m_2\ddot{u}_2(t) + K_{x2}u_2(t) = 0, \\
& m_2\ddot{v}_2(t) + K_{y2}v_2(t) = -m_2(\ddot{Y}(t) + \ddot{v}_1(t)), \\
& I_2\ddot{\theta}_2(t) + K_{\theta 2}(t)\theta_2(t) = -I_2\ddot{\theta}_1(t)\text{.....or....}[-I_2(\ddot{\Theta}(t) + \ddot{\theta}_1(t))]\text{....or....}[-I_2\ddot{\theta}_1(t)]
\end{aligned}
\tag{2}
$$

$$
\begin{aligned}
& m_1\ddot{u}_1(t) + K_{x1}u_1(t) - K_{x2}u_2(t) = 0, \\
& m_1\ddot{v}_1(t) + K_{y1}(v_1(t) - e_{x1}\theta_1(t)) - K_{y2}v_2(t) = -m_1\ddot{Y}(t)\text{....or....}[-m_1(\ddot{Y}(t) - e_{x1}\ddot{\Theta}(t))] \\
& \text{....or....}[-m_1\ddot{Y}(t) + F_{\mathrm{by}}] \\
& I_1\ddot{\theta}_1(t) + K_{\theta 1}\theta_1(t) - K_{\theta 2}\theta_2(t) - K_{y1}e_{x1}v_1(t) = 0\text{...or...}[-I_1\ddot{\Theta}(t)]\text{....or....}[F_{\mathrm{by}}r_x]
\end{aligned}
\tag{3}
$$

The ordinary system describing simple seismic response is extended for inclusion the control components. Expressions in brackets mean changes due to control, the first one for yaw control, the second one for brace control. Stiffness matrix includes participation of lateral and torsion stiffness members. The parametric study of translate-torsion vibration in Juhásová [1] describes the changes in seismic response and strain-stresses distribution throughout the structural elements. Stresses and deformation in edge elements including shear in torsion are the primary reason of their failure. Such failure appears at lower seismic input in comparison to the seismic carrying capacity of symmetrical systems with the same lateral stiffness. The improvement can be reached either through control torsion input at the base (if there exist conditions to arrange it e.g. in the framework of base isolation system) or through so called "intelligent brace". Both variants were numerically analysed and afterwards tested on MASTER shaking table in ISMES. However, physical principles of dynamic behaviour in these two cases are rather different. In the case of control through base torsion input the changes in natural frequencies of the superstructure are negligible. The partial effect can appear there due to changes in boundary conditions. The case of "intelligent brace" control represents the stiffness-damping variation in time with respective temporary changes in natural frequencies of the superstructure.

The system under control tries to optimise the response that finally means the increase of the total seismic resistance of the structure. Before running the tests the respective analytical models were built and verified by numerical studies and numerical experiment for chosen seismic inputs. Seismic inputs represented: Alaska 1972 earthquake, Sitka record NS acting in *y*-direction; Northridge 1994 earthquake, record at Moorpark; and Central Italy 1997 earthquake, record at Nocera. 0 dB means full actual earthquake. See also Figures 5, 6 and 7.

The experimental results were obtained from seismic tests carried out with different model configuration (without brace, with stiff brace, with active controlled brace, with two braces – stiff and active) and increasing intensity of seismic loading. The control approaches with base torsion input (yaw control) ASI and TVC were applied and realised by predetermined input (Juhásová et al. [8]). The filtering of ASI control input reflected the measured natural frequencies and modal contributions of translate seismic input and yaw control input.

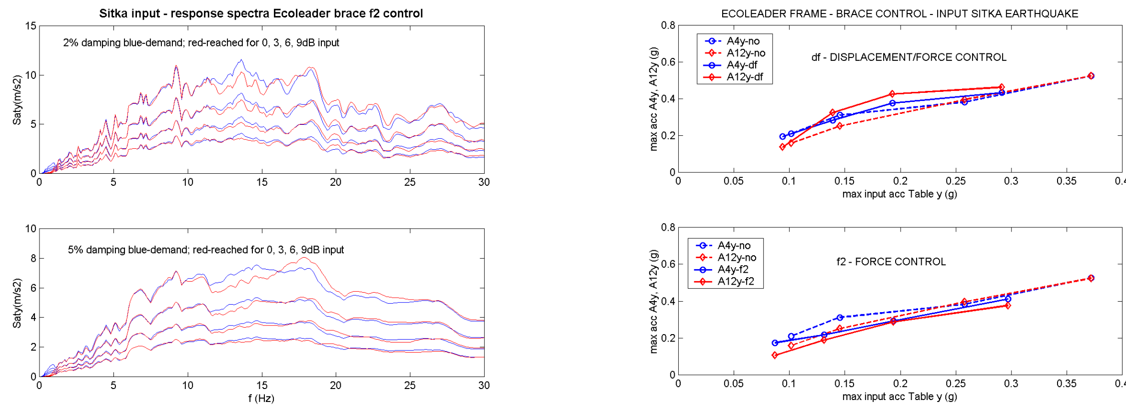

Figure 5. Response spectra and max floor accelerations during the tests: Sitka based seismic input

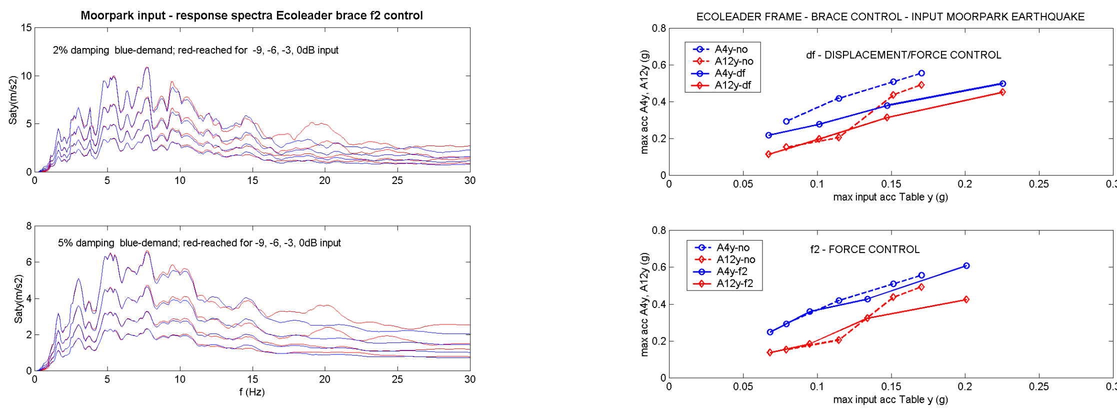

Figure 6. Response spectra and max floor accelerations during the tests: Moorpark based seismic input

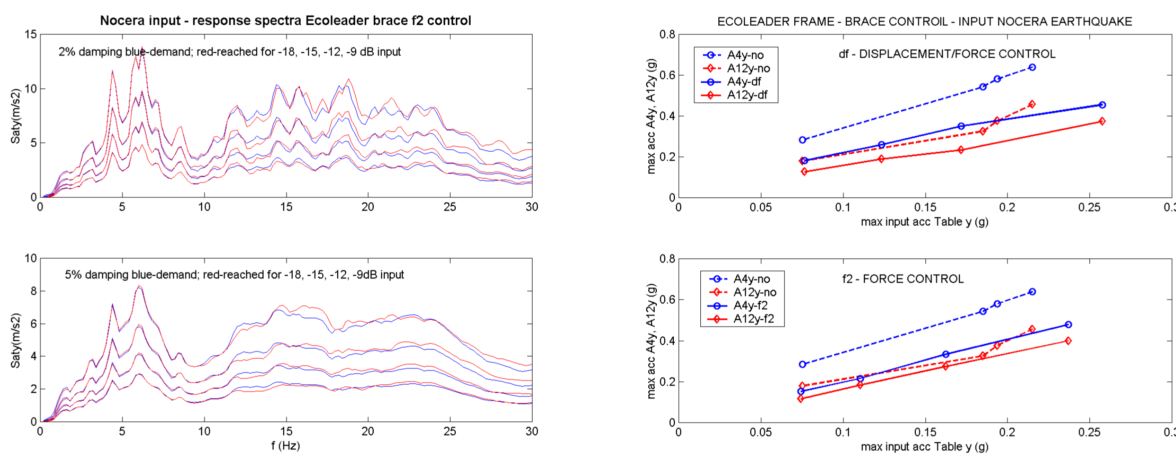

Figure 7. Response spectra and max floor accelerations during the tests: Nocera based seismic input

Measured time histories of strains and absolute deflections of the frame storeys show the positive contribution of the control. Strains in critical sections were directly measured. Their maximum values are reported in Figure 8 (left) comparing the original model without any control, model with ASI control and model with TVC control. Similar comparison was realised for brace control approach. Brace control represents interference of purposely modified dynamic force from another independent hydraulic system. The seismic excitation corresponds to Sitka 0dB NS earthquake and was applied in y direction.

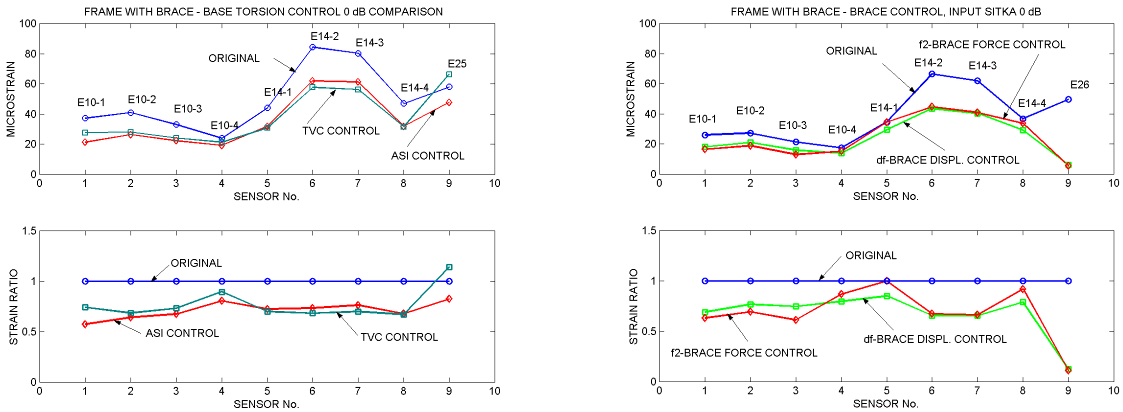

Figure 8. Max strains in the frame at Sitka input 0dB, left – S1+yaw control; right – S2+brace control

Achieved effective behaviour represents decrease of stresses in critical sections up to 40 % or more. Forecasting from calculations was even larger. The total energy coming into the tested structure was remarkably reduced. The same effect can be observed on cumulative characteristics (e.g. Juhásová [9]). The cumulative absolute velocity $V_{\mathrm{cum,abs}}$ like supporting characteristic is frequently used nowadays

$$V_{\mathrm{cum,abs}} = \int_{t_1}^{t_2} \mathrm{abs}(V(t))\mathrm{d}t = \int_{0}^{T} \mathrm{abs}(V(t))\mathrm{d}t \tag{4}$$

and represents the total cumulation of velocities or stresses due to dynamic effects with the same weight given to large or small amplitudes. It can be applied also on storey drifts in view of displacements and rotations, see Figures 9 and 10.

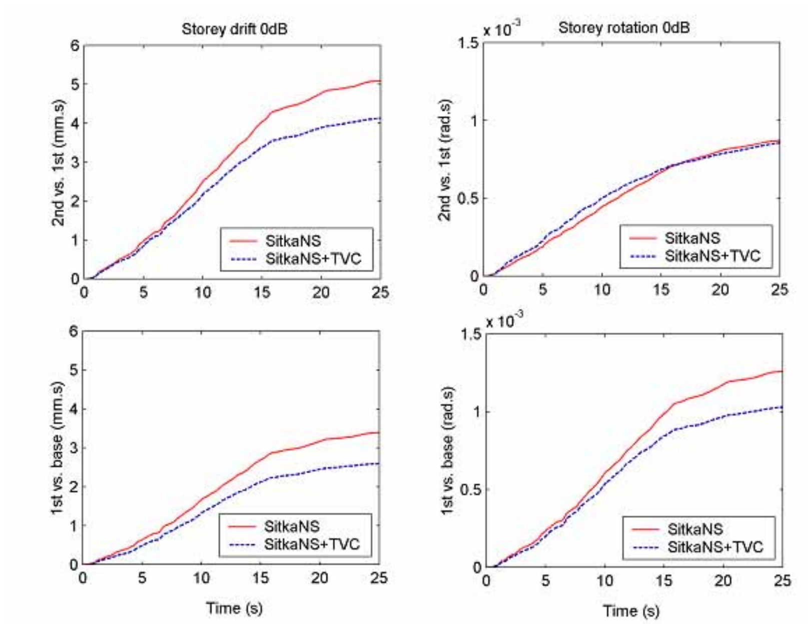

Figure 9. Cumulative storey drifts in displacements and rotations for Sitka input: SitkaNS – stiff brace, no control; SitkaNS+TVC – stiff brace and yaw TVC control at the base of frame model

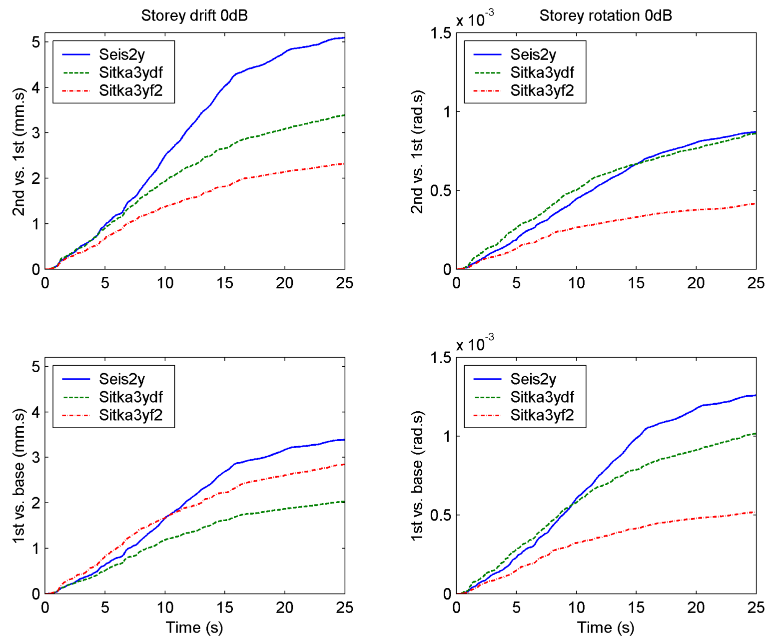

Figure 10. Cumulative storey drifts in displacements and rotations for Sitka input: Seis2y – stiff brace, no control; Sitka3ydf – displ./force df brace control; Sitka3yf2 – force f2 brace control

Table 2. Maximum measured strains in columns E10, E14 and in stiff brace E25

Maximum measured microstrains in the second storey					
Excitation Sitka 0dB	E10-1	E10-2	E10-3	E10-4	-
Original, no control, S1	37.18	40.96	33.03	23.91	-
ASI yaw base control	21.31	26.34	22.36	19.37	-
TVC yaw base control	27.61	28.08	24.16	21.38	-
Maximum measured microstrains in the first storey					
Excitation Sitka 0dB	E14-1	E14-2	E14-3	E14-4	E25
Original, no control, S1	44.01	84.35	80.31	47.02	58.06
ASI yaw base control	31.92	62.01	61.26	31.85	41.85
TVC yaw base control	30.78	57.76	56.22	31.50	66.37

Table 3. Maximum measured strains in columns E10; E14 and in control brace E26

Maximum measured microstrains in the second storey					
Excitation Sitka 0dB	E10-1	E10-2	E10-3	E10-4	-
Original, no control, S2	26.13	27.37	21.32	17.52	-
intelligent brace control **df**	18.06	21.03	15.92	13.94	-
intelligent brace control **f2**	16.51	18.99	13.05	15.21	-
Maximum measured microstrains in the first storey					
Excitation Sitka 0dB	E14-1	E14-2	E14-3	E14-4	E26
Original, no control, S2	34.55	66.52	61.88	36.76	49.64
intelligent brace control **df**	29.42	43.60	40.42	29.09	6.19
intelligent brace control **f2**	34.56	44.78	41.02	33.80	5.46

CONCLUSIONS

Presented theoretical, numerical and experimental analyses of control gave results that indicate remarkable mitigation of the seismic response. Different control algorithms were successfully adapted and calibrated. Experimental results confirmed acceptable dynamic behaviour of the tested models. This was reached both by base torsion control tests and also by successful tests with the use of intelligent brace control. The applications secure the increase of safety and reliability of existing and newly built structures. Consequently, also the secondary transfer of seismic inputs through floors to equipment recorded effective improvement. The designer should decide whether using of traditional upgrading measures in view of stiffness-mass-damping adjustments, or promising integrity improvements could secure sufficient degree of structural safety and the appropriate life time. Response reduction systems developed at the boundaries of civil, mechanical and electronic engineering create another group of tools for the increase of structural safety. Robustness of mechanical-structural systems, reliability and cost aspects and next developments will influence the penetration of these advanced technologies into everyday construction industry.

Acknowledgements
The research was mainly founded by European Commission in the framework of ECOLEADER Studies, Project FP5, HPRI-CT-1999-00046 and partially by VEGA Project 2/4078/24. The financial support is gratefully acknowledged.

REFERENCES

1. Juhásová E. "Seismic Effects on Structures." Amsterdam: Elsevier, 1991.
2. Benchoubane H, Stoten DP. “The decentralized minimal controller synthesis algorithm.” Int. Journal of Control 2000; 56(4): 967-83.
3. Juhás M. “Development of real time control system for 2DOF shaking table.” Proceedings of Conference on Mechanical Engineering 2000. Bratislava: FME SUT, 2000: 2/47–52.
4. Loh CH, Lin PY, Chung NH. “Experimental verification of building control using active bracing system.” Earthquake Engng. and Struct. Dyn. 1999; 28(10): 1099-119.
5. Molina J, Magonette G, Pegon P. “Assessment of systematic experimental errors in pseudodynamic tests.” Proceedings of 12th European Conference on Earthquake Engineering 2002, London, UK. Paper no. 525. Amsterdam: Elsevier, 2002.
6. Bergamo G, Franchioni G. “The structural dynamics testing laboratory of Enel.Hydro – Ismes.” Casciati F, Editor. Proceedings of the 3rd World Conference on Structural Control 2002, Como, Italy. Chichester: Wiley, 2003; 2: 997-1006.
7. Juhásová E, Juhás M, Svrček V. “The real time control for earthquake engineering applications.” The Bulletin of the European Association for Earthquake Engineering 2001, 20(1): 39-40.
8. Juhásová E, Juhás M, Franchioni G, Bergamo G. “Control of seismic vibration near the base of asymmetrical structures.” Proceedings of Conference on Seismic Isolation, Passive Energy Dissipation and Active Control of Vibrations of Structures 2001, Assisi, Italy. Bologna: GLIS/ENEA, 2002; 2: 321-28.
9. Juhásová E. “Classical and latest tools for determination of dynamic resistance capacity.” Konvalinka P, Máca J. Editors. CTU Reports I, **7**(2) Contributions to Computational and Experimental Investigation of Engineering Materials and Structures - Structural Dynamics. Prague: CTU, 2003: 301-10.