THE CONTRIBUTION OF CONTROL TO EARTHQUAKE MITIGATION

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Abstract

The progress in active, hybrid and semi-active vibration control technique in various countries has already led to some promising results, not only for the control of wind or machinery induced vibration, but also for the seismic protection. Necessary verifications of reliability and safety interfere with reasonable initial and service costs. Under these circumstances, the control software is a crucial part of the methodology and vibration control techniques. The paper deals with the results of international research related to those structures that due to different reasons are more vulnerable under the adverse earthquake excitation. For verification of such systems reliability, the real time control algorithm and software were developed and analysed in extensive numerical studies. The control device was the subject of seismic tests while using variable seismic input and different structure composition.

The prototype for numerical and experimental verification of the proposed procedures was chosen like a steel frame of two storeys, one bay and different brace composition in the first storey. The aim of control was to decrease those vibration components that could substantially influence the failure risk of a respective structure. The series of tests proved essential improvement of the seismic response in comparison with the original structure composition. The questions and tasks are open for future research and technology development, prevailingly in the design and optimisation of suitable devices and the appropriate choice of control hardware and software. The obtained numerical and experimental results have shown a positive effect of applied measures and create a base for future practical use.

INTRODUCTION

The construction of new structures, upgrading, strengthening and repair of existing ones are based on the decision what will be the full or remaining life time. What degree of resistance capacity should be provided to meet combination of dead and imposed loads and future accidental impacts of seismic or other origin? When, where and how strong will be the next earthquake? What is the risk we accomplish with the structure design and execution? What are the uncertainties resulting from the estimates of loading, structure materials and systems, analysis and human errors? Which simplified methods are sufficiently reasonable to replace more sophisticated calculations? What is the answer from observations and experimental measurements either on full scale structures or on large scale models? Such questions appear at the design of structures in seismic but also in non-seismic regions.

Any structure shall be designed such that deterioration over its design working life does not impair the performance of the structure below that intended. Environmental effects and anticipated level of maintenance should be taken into account. However, the environmental conditions shall be identified at the design stage so that significance can be assessed in relation to durability and adequate provisions can be made for protection of the materials used in the structure. The environmental effects can influence the structure safety both in view of action changes and the deterioration of material properties as well. 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.

DYNAMIC RESISTANCE CAPACITY

The analytical design model should be developed, leading to the derivation of a resistance function, based on the observation of actual material behaviour and on theoretical considerations. The validity of such model should be checked by means of a statistical interpretation of all available test data. The analytical structural model to be used for determining the dynamic action effects shall be established taking into account of all relevant structural members, their masses, strengths, stiffness and damping characteristics, and all relevant non-structural members with their properties. The procedure for determining the design resistance starts from design values of material or product properties including the deviations likely to appear.

The expected modes of failure and related calculation models should be estimated and described. In general, the structural member can possess a number of fundamentally different failure modes. Structural behaviour can depend upon the effects of one or more actions that will not be varied systematically. The response is interconnected with the resistance of materials used and both can depend on time and duration effects, scale and size effects, different environmental, loading and boundary conditions, and material degradation effects.

New materials in majority need the statistical determination of resistance models. This can be done for new material alone or for composite systems using combinations of traditional and new materials. Not only new materials but also traditional materials have recorded changes in their properties that should be taken into account when the resistance is to be defined. The contribution of appropriately chosen new materials used in composite system with traditional ones can be significant, e.g. Juhásová et al., 1998, Severn et al., 2000, Juhásová et al., 2000, Sofronie, 1997, Sofronie et al., 2003.

Theory of strains and stresses in elastic and plastic bodies and media describes the options and conditions for the failure, in general dependent on the contribution of shear and axial stresses and strains in their tensors or in tensors of respective velocities. Properties of loading in space and time and strength limits, with the contribution of damping and redistribution of carrying capability, control ultimate resistance of the structure. For securing the proper progress, first of all should be clear in the borders of static resistance usually related to vulnerable sections. Procedures proposed for simplified approaches like "pushover analysis method", see e.g. Fajfar, 1999, Priestley, 1997, could be adapted to some degree for the determination of design carrying capacity of new composite systems. The important issues are interconnected with the structural integrity that is the appropriate tool helping the structure to overcome the effects of large earthquakes, terrorist attacks or another accidental events.

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 et al., 2000, Loh et al., 1999, Juhás, 2000, Molina et al., 2002). 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 tested in the presented 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 in real time like simulation and 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 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.

REALISED TESTS

The model was chosen as a two storeys steel frame, one bay, with asymmetrical brace situated in the first storey. The view of the model is presented in Fig. 1. 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 dynamic response increases or decreases in dependence on brace stiffness and spectral properties of the seismic input. The intended improvement of the response can be reached either through yaw control at the base or through "intelligent" brace.

Fig. 1: General view of tested frame model, left – with stiff brace, right – with the brace control

Calculation modifications 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. Position of sensors and impact points is given in Fig. 2.
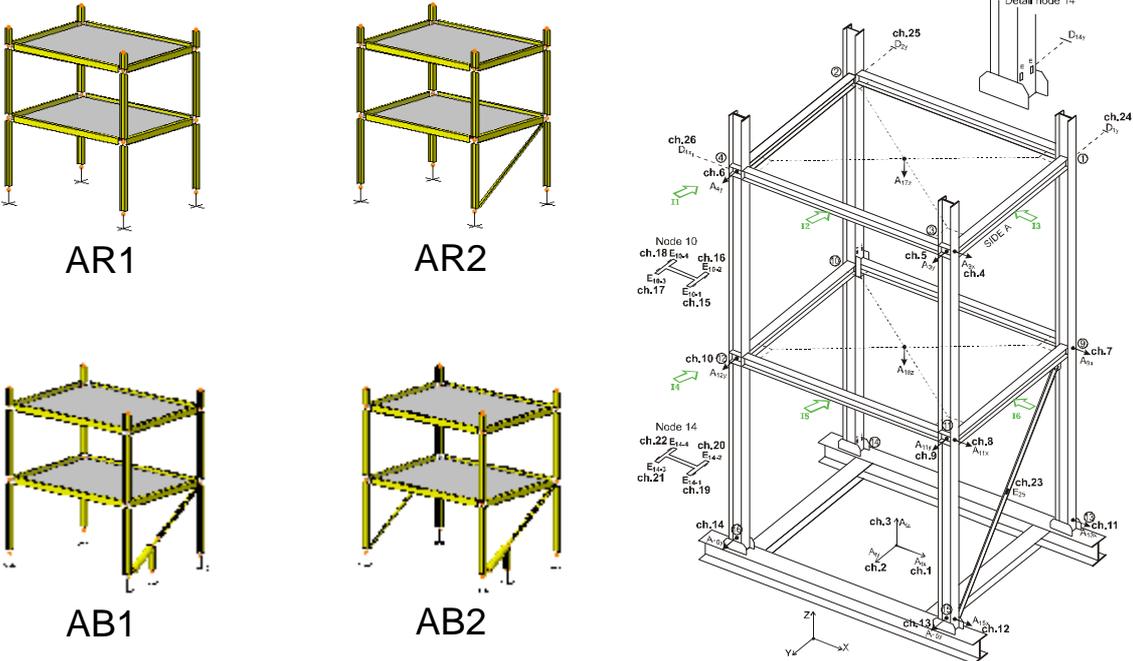

Fig. 2: Used tested frame model compositions, impact points and instrumentation

The analysis and 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.

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., 2001. The sources of outside excitation were either impacts or external seismic steady vibration. Fig. 3 shows the jack test composition and the results obtained.
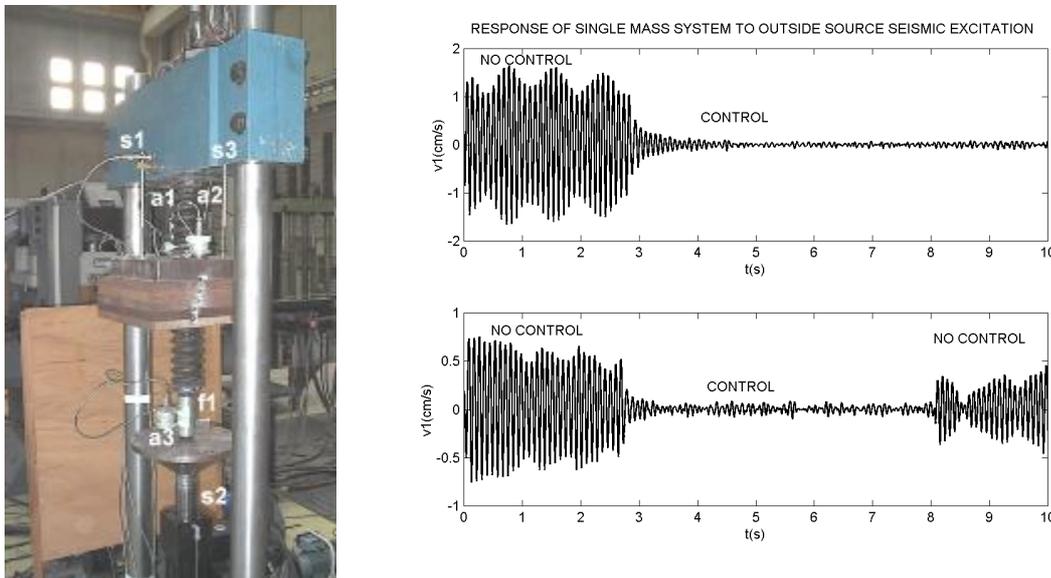

Fig. 3: The jack test composition and the effect of control in case of external steady excitation

ANALYTICAL STUDIES

In case of asymmetrical structures the stiffness centre does not coincide with the centre of mass. The result is the presence of dynamic moments, which introduce torsion components into the response of the structure in addition to the translate displacements. Deformation of any participating vertical element consists of translate and torsion components. If equations of motion follow the centres of concentrated floor masses, the seismic excitation in *y* direction is described by a system:

$$m_2 \ddot{u}_2(t) + K_{x2} u_2(t) = 0,$$
$$m_2 \ddot{v}_2(t) + K_{y2} v_2(t) = -m_2(\ddot{Y}(t) + \ddot{v}_1(t)),$$
$$I_2 \ddot{q}_2(t) + K_{q2}(t) q_2(t) = -I_2 \ddot{q}_1(t) ....or....[-I_2(\ddot{\Theta}(t) + \ddot{q}_1(t))]....or....[-I_2 \ddot{q}_1(t)]$$

(1)

$$m_1\ddot{u}_1(t) + K_{x1}u_1(t) - K_{x2}u_2(t) = 0,$$

$$m_1\ddot{v}_1(t) + K_{y1}(v_1(t) - e_{x1}q_1(t)) - K_{y2}v_2(t) = -m_1\ddot{Y}(t)....\text{or}....[-m_1(\ddot{Y}(t) - e_{x1}\ddot{\Theta}(t))]$$

$$....\text{or}....[-m_1\ddot{Y}(t) + F_{by}]$$

$$I_1\ddot{q}_1(t) + K_{q1}q_1(t) - K_{q2}q_2(t) - K_{y1}e_{x1}v_1(t) = 0...\text{or}...[-I_1\ddot{\Theta}(t)]....\text{or}....[F_{by}r_x]$$

$$(2)$$

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, 1991 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 (Juhásová et al., 2002). Seismic input represents Alaska 1972 earthquake, Sitka record N-S acting in *y*-direction; 0dB means full actual earthquake, Fig. 4.
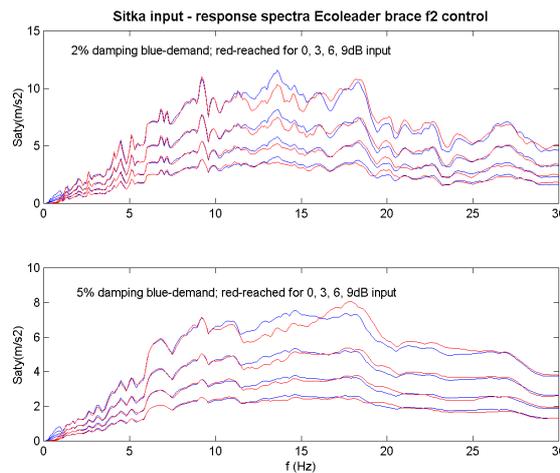

Fig. 4: Response spectra of original and simulated seismic input for 2% and 5% damping

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., 2002). The filtering of ASI control input reflected the measured natural frequencies and modal contributions of translate seismic input and yaw control 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 5 (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 in Fig. 5 corresponds to Sitka 0dB NS earthquake applied in *y* direction.
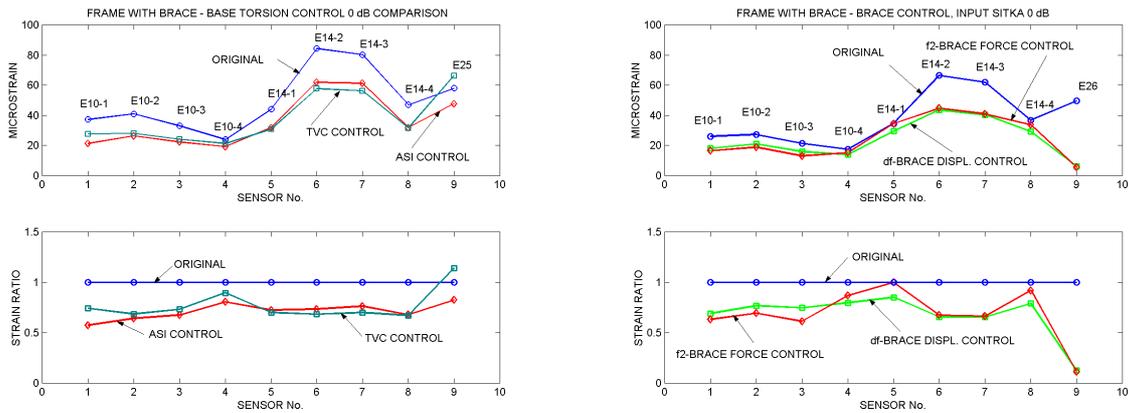

Fig. 5: Max strains in the frame at Sitka input 0dB, left – S1+yaw control; right – S2+brace control

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.

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, 2003). The cumulative absolute velocity $V_{\text{cum,abs}}$ like supporting characteristic is frequently used nowadays

$$V_{\text{cum,abs}} = \int_{t_1}^{t_2} \text{abs}(V(t))\mathrm{d}t = \int_{0}^{T} \text{abs}(V(t))\mathrm{d}t \tag{3}$$

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, see Figs. 6 and 7.
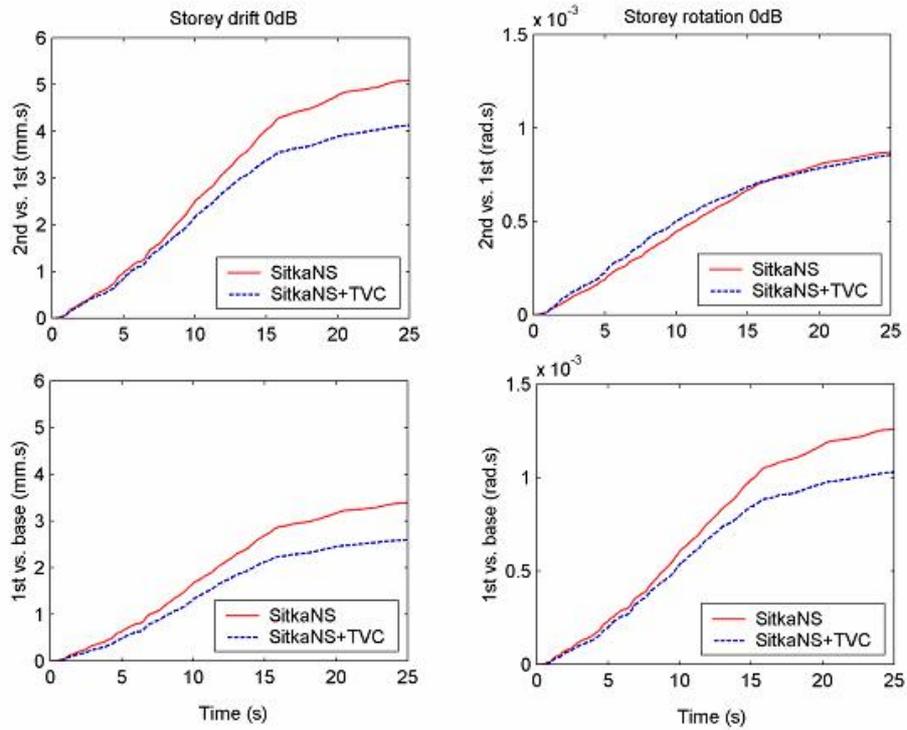

Fig. 6: Cumulative storey drifts in displacements and rotations for Sitka input: SitkaNS – stiff brace, no control; SitkaNS+TVC – stiff brace and yaw **TVC** control at the base of frame model
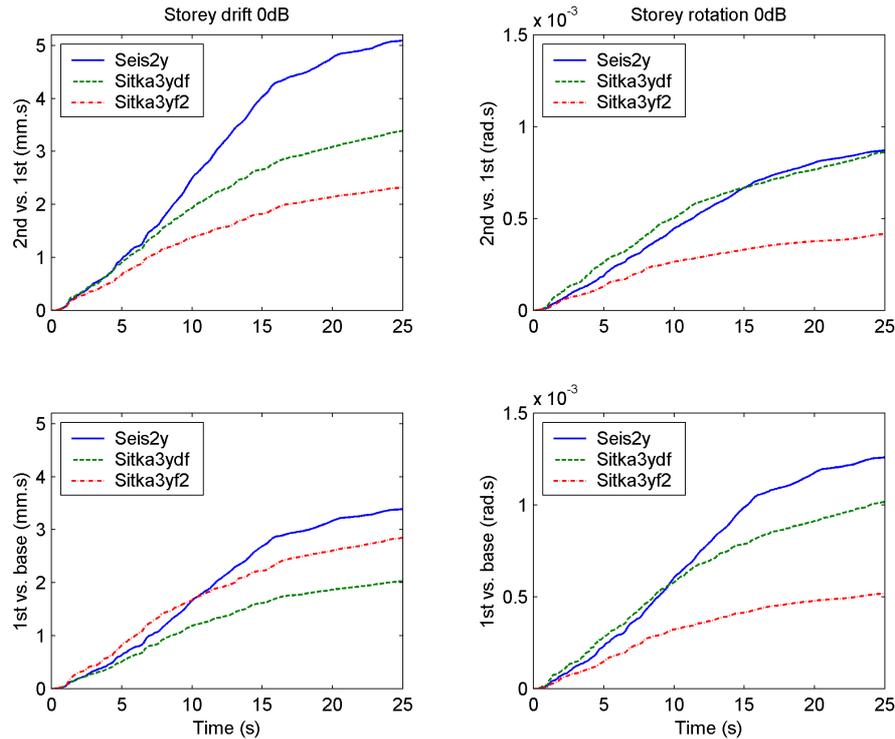

Fig. 7: Cumulative storey drifts in displacements and rotations for Sitka input: Seis2y – stiff brace, no control; Sitka3ydf – displacement/force **df** brace control; Sitka3yf2 – force **f2** brace control

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.

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