Implementing Innovative Ideas in Structural Engineering and Project Management
Edited by Saha, S., Zhang, Y., Yazdani, S., and Singh, A.

ISBN: 978-0-9960437-1-7

A COLUMN SYSTEM WITH ARTICULATED JOINTS AND ELASTICALLY EMBEDDED DIAPHRAGMS

JIRI WITZANY[1], DANIEL MAKOVICKA[2], RADEK ZIGLER[1], TOMAS CEJKA[1], STANISLAV POSPISIL[3], and ALES POLAK[1]

[1]*Dept of Building Structures, Czech Technical University in Prague, Prague, Czech Republic*
[2]*Klokner Institute, Czech Technical University in Prague, Prague, Czech Republic*
[3] *The Institute of Theoretical and Applied Mechanics, Prague, Czech Republic*

The spatial stability and controlled dynamic characteristics of an articulated precast column system are secured by thin-walled reinforced concrete diaphragms elastically embedded in some bays by means of special damping bearings. The intensity and the range of the load-bearing system's response to dynamic (e.g. seismic) effects and vibrations are achieved by the stiffness adjustment of damping bearings. The stiffness of damping bearings may also be adjusted during exploitation. The designed structure with an elastically embedded diaphragm has been exposed to dynamic testing whose results are presented in the article. Another significant characteristic of the precast structure is its dry assembly and potential disassembly and relocation to another site. The experimental and theoretic analyses performed have confirmed the assumptions for the system's application in areas with the occurrence of natural seismicity.

Keywords: Frame, Dynamic characteristics, Bearings, Natural oscillation, Forced oscillation.

1 INTRODUCTION

The investigated load-bearing reinforced concrete precast system for multi-storey buildings is characterised by demountable pin joints with dry assembly and potential disassembly and relocation to another site. Another significant characteristic of the precast structure is its ability to absorb the strain energy exerted by dynamic effects reducing thus their intensity to a required level.

The controlled dynamic characteristics of the load-bearing column system form prerequisites for the system's application under extreme conditions and situations allowing, to a considerable extent, eliminating the dynamic and seismic effects due to human activity, traffic, construction and production activity (technical and induced seismicity), or natural seismic impacts. Besides eliminating the intensity of dynamic effects to a level that will not cause a failure of the structure or its parts, through compensation elements embedded in joints and capable of absorbing energy with specific dynamic properties, another significant characteristic of these joints is the possibility of reducing the load-bearing system's response to the effects of traffic, construction activity, industrial activity, etc. The system may analogically be applied in areas with impaired foundation conditions, underground traffic, in undermined regions and in regions with a high probability of the occurrence of natural seismicity. The joint of columns ("column – column") is designed using the principle of adjusting screws fitted with mounting and, at the same time, adjustment nuts for levelling the higher-storey columns to the desired height and vertical position. The column foot houses special (neoprene, polypropylene) dowels passing through holes in the steel plate. To eliminate vibrations from a lower to a higher storey and reduce the load-bearing system's response to dynamic effects, the stiffness of the "column – column" joint is reduced. The screws levelled in height and anchoring pins protruding from the lower storey column head are used for mounting a steel distribution plate fitted with a rubber bearing with appropriate stiffness so that vibrations of some frequencies are damped, or dynamic characteristics of the load-bearing column system are modified in a desired way (Witzany *et al*. 2009, 2013, Makovicka *et al*. 2011). The spatial stability and controlled dynamic characteristics of an articulated precast column system are secured by thin-walled reinforced concrete diaphragms elastically embedded in some bays by means of special damping bearings. The intensity and the range of the load-bearing system's response to dynamic (e.g., seismic) effects and vibrations are achieved by the stiffness adjustment of damping bearings. The stiffness of damping bearings may also be adjusted during exploitation. The spatial stability of the articulated precast column system is secured by precast reinforced concrete diaphragms or specially shaped stiffening structures (e.g., A-shaped), or steel stiffening structures (steel ropes or tubes bracing diagonally articulated joints of columns and girders) embedded in some "frame" bays, or between columns perpendicular to the frame bay in the case of unidirectional arrangement of "frames". In bracing articulated frames with embedded reinforced concrete thin-walled diaphragms, the columns and girders with diaphragms are mutually discretely interconnected via contact rubber bearings, whose distribution and stiffness rely on the magnitude and intensity of static or dynamic loads. It is, above all, the shear stiffness, or the number and distribution of rubber bearings that is the essential factor affecting the dynamic properties of the articulated column system (Figure 1).

2 EXPERIMENTAL AND THEORETICAL ANALYSIS OF DYNAMIC CHARACTERISTICS OF AN ARTICULATED FRAME BAY WITH A DIAPHRAGM – COMPUTATIONAL MODEL

The objective of experimental verification was research into the response of a frame structure with a stiffening diagram to repetitive deformation effects exerted by horizontal forces (so-called pseudodynamic test, Figure 1, Table 1). The test configuration of a frame bay segment in a 60% scale was composed of two precast reinforced concrete columns with dimensions of 180x180 mm 2500 mm in height, two cross bars (girders) with dimensions of 240 x 180 mm 2860 mm in height and an elastically embedded stiffening diaphragm with dimensions of 2800 x 1650 x 50 mm, connected to the frame cross bars by elastic bearings.

The experimental setup was loaded by the MTS 244.31 hydraulic press (maximum force of 250 kN, maximum dynamic deformation range of 254 mm), by induced deformation of 1 to 5 mm in magnitude with frequencies of 0.1 to 20 Hz. The loading pattern was of a saw type. 14 linear variable differential transformers (LVDT) were mounted in the experimental setup. They measured the force necessary for exerting the required displacement-controlled loading, absolute frame deformations (at the upper and lower free end of the setup) and relative displacements between columns and girders (inclined transformers in the corners of the setup), columns and the diaphragm (horizontal transformers) and girders and the diaphragm (vertical transformers).

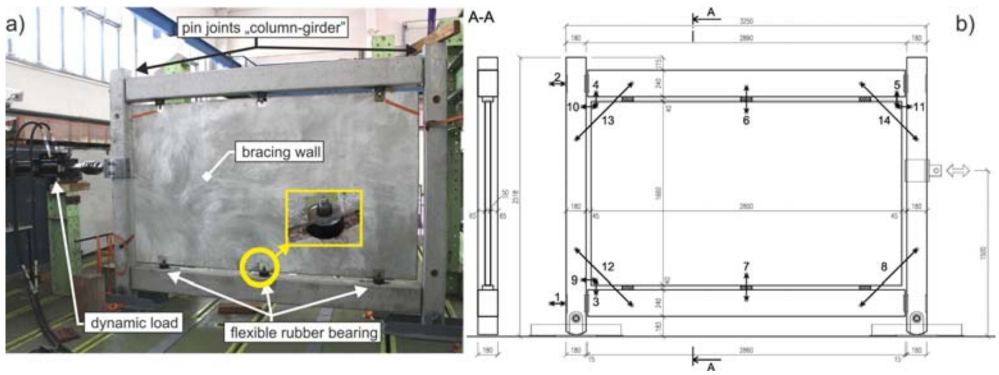

Figure 1. a) Articulated frame bay with an embedded stiffening diaphragm, contact rubber bearing, b) Experimental setup, LVDT arrangement in the experimental setup (*Legend: - frame bay columns have articulated supports at the bottom; articulated connection of cross bars to columns; rubber silent blocks are fixed to cross bars, the contact with the diaphragm is articulated; displacement in the transverse y-direction is prevented in the whole structure).*

Table 1. Overview of loading states.

	Frequency [Hz]							
	0.1	**0.5**	**1.0**	**2.0**	**5.0**	**10.0**	**15.0**	**20.0**
Amplitude [mm]	1 - 5	1 - 5	1 - 5	1 - 5	1, 2, 2.7	0.5, 1	0.5	0.45

2.1 Mechanical Characteristics of Rubber Silent Blocks (Bearings)

The rubber inside the silent blocks is cylindrical-shaped with a diameter of 100 mm and a height of 40 mm. This is in correspondence with the following rubber parameters (Figure 2):

- For stiffness of 43 SH the elastic modulus E = 5092 kPa for rubber compression by 1.5 mm, Poisson's ratio is estimated as 0.40;
- For stiffness of 68 SH the elastic modulus E = 20372 kPa for rubber compression by 1.5 mm, Poisson's ratio is estimated as 0.40.

The elastic moduli of rubber correspond to the compression of the rubber cylinder by ca 0.5 to 2.5 mm. The bulk density of rubber was estimated as 500 kg/m^3.

The frame bay with a diaphragm with an articulated connection braced by silent blocks against the upper and lower cross bar was modelled as a 3D model in the Scia Engineer computational programme. The dimensions of the frame bay and its sections were adopted from the bay design for its experimental verification. The material considered for the columns, cross bars and the diaphragm was concrete C50/60. The columns, cross bars and the diaphragm were modelled by plate elements, while the rubber silent blocks by bar elements. The replacement of joints between the columns and cross bars was modelled by bar elements.

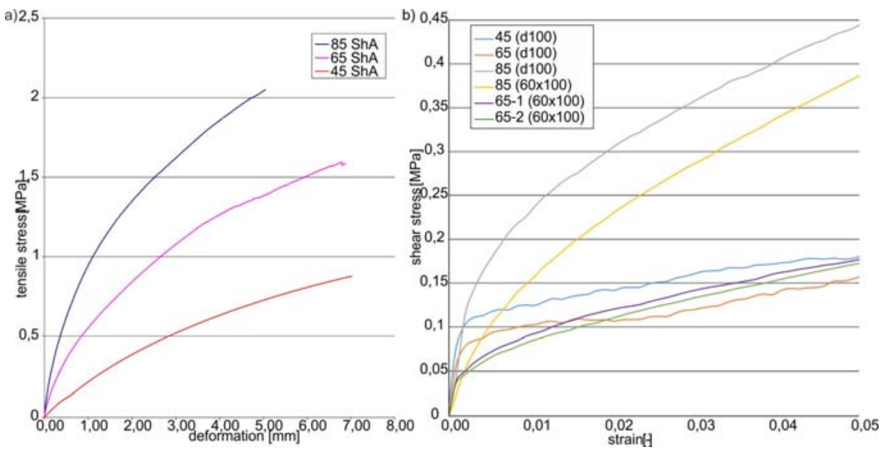

Figure 2. Experimentally identified working diagrams of rubber bearings varying by stiffness – a) tensile stress – deformation, b) shear stress – strain.

During the loading rise time to a dynamic force value of 0.009 kN, the model starts vibrating until the vibrations stabilise at a static deflection of ca 0.85 mm. After an instantaneous excitation drop to 0 (static deflection release), the model vibrates with an amplitude of 1.55 mm in the horizontal direction. The free vibration time pattern corresponds to the first natural frequency $f_{(1)}$. The damping of this vibration (according to Figure 3) corresponds to the logarithmic decrement of 0.340 (5.4% of critical damping).

Due to a low loading force and low natural frequencies, the vibration of columns and cross bars only corresponds to the turning (columns) or displacement (cross bars) of these members. The bending of these members would only occur under dramatically higher frequencies (see calculated natural frequencies).

2.2 Natural Oscillation

Based on the natural oscillation calculation, the lowest natural frequencies and normal modes of vibration for a frame bay were specified (Table 2). The comparison of natural frequencies for both types of silent blocks evidently shows that stiffer silent blocks are likely to be applied on a larger scale in common construction practice. The diaphragm displacement in the transverse direction is likely to find application in horizontal seismic excitation of buildings or in the case of wind effects in tall structures. Both will depend on their actual tuning.

2.3 Forced Oscillation

According to Fig. 2, it was assumed that the frame bay would be loaded with the horizontal dynamic force F_x = 0.009 kN on one of the columns during the experimental verification. A rectangular time pattern with a time rise was selected for this loading force. The time function in the interval of 0 s to 3.0 s is linear growing from 0 up to a dimensionless amplitude of 1.0; in the interval of 3.0 to 7.0 s the time function is constant equalling 1.0; at the time of 7.0 s it drops to 0 again and the frame bay structure finishes vibrating by natural oscillation (Figure 4). Forced oscillation was calculated for a length of 19.0 s with a time step of 0.010 s. The damping of the structure was estimated as 5% of critical damping due to rubber silent blocks (logarithmic decrement of 0.314). The calculated time pattern of the setup deflection at the application point of the dynamic force F_x is presented in Fig. 3.

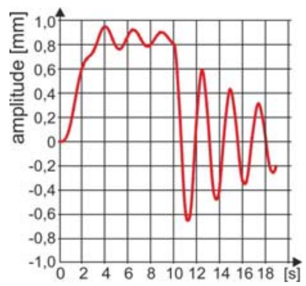

Figure 3. Deflection time pattern for loading with the force F_x and after the frame bay release (theoretical analysis).

Table 2. Natural vibration frequencies of a frame bay with a diaphragm and six silent blocks.

No. *i*	**Natural frequency $f_{(i)}$ [Hz]**		**Normal mode of vibration**
	Silentblocks SH 43	**Silentblocks SH 68**	
1	0.25	0.38	transverse vibration, columns and the diaphragm in the same direction
2	0.82	1.61	transverse vibration, columns and the diaphragm in opposite directions
3	1.44	-	diaphragm vertical vibration in the *z* direction
3	-	2.79	diaphragm turning in the frame plane
4	1.45	-	diaphragm turning in the frame plane
4	-	2.87	diaphragm vertical vibration in the *z* direction
5	49.50	49.55	upper cross bar bending
6	50.49	50.54	lower cross bar bending

3 CONCLUSIONS

Under the conditions of adequate tuning of the frame setup corresponding to the selected silent blocks and the diaphragm size, the diaphragm embedded in a frame bay allows significant damping of the structure of the building in which this member is placed. In this case, an elastically embedded diaphragm functions as a dynamic damper (shock absorber) within the whole structure of the building. The characteristics of this vibration damper may be affected both by the used absorbers and the weight of the diaphragm. The advantage of this solution is the fact that the bay with the diaphragm behaves like a stiffened structure and also like a vibration damper, as was specified above. The design of the silent block stiffness and the diaphragm weight must be carried out with regard to the required frequency of the whole structure which should be damped by this dynamic damper.

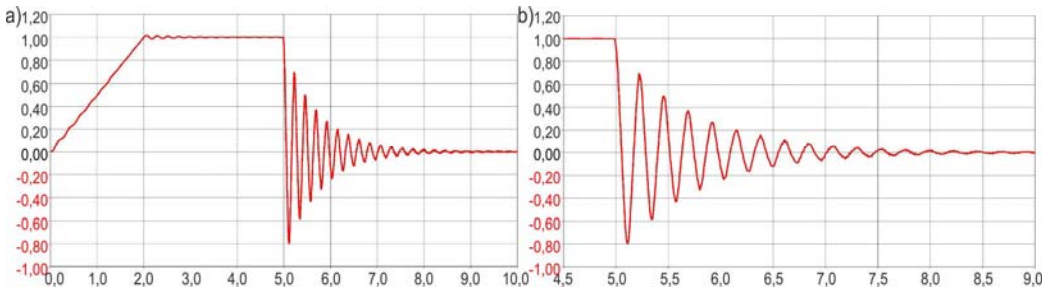

Figure 4. a) Forced oscillation time pattern of the structure for setup 08 for rubber 45 ShA loaded by the dynamic force F_x (entire loading pattern), b) Forced oscillation time pattern of the structure for setup 08 for rubber 45 ShA loaded by the dynamic force F_x (afterpulsing, experimental analysis).

The damping of a structure with an embedded diaphragm ("dynamic system" of damping) proceeds in the same way as in a dynamic damper supposing that the natural frequency of the diaphragm approaches the natural frequency of the flexural vibration of the whole structure. This may be achieved by the dynamic system's tuning – a suitable selection of the diaphragm weight and dynamic characteristics of bearings. In the opposite case, dramatically different frequencies of the structure and the diaphragm ("dynamic damper") may act like a vibration amplifier.

Acknowledgments

The paper was written with support from TA02010837 "Multipurpose dismantleable prefabricated reinforced concrete building system with controlled joint properties and the possibility of repeated use."

References

Makovička, D., and Makovička, D., Vibrobase insulation of a building ex-cited by the technical seismicity effect of tube railway operation. In *Earthquake Resistant Engineering Structures VIII*, Brebbia, C.A., Maugeri, M. (Ed.), 79-88, WIT Press, Southampton, 2011.

Witzany, J. *et al.*, Prefabricated Planar Structure of a Multi-Storey Building Exposed to Cyclic Load and Engineering Seismicity. In *Proceedings of the Fifth International Structural Engineering and Construction Conference*, *Las Vegas, 21-27 September 2009*. Leiden: CRC Press/Balkema, p. 339-344, 2009.

Witzany, J., Čejka, T., and Zigler, R., Dismantleable joints of load-bearing reinforced concrete units of prefabricated concrete building system with controlled stiffness. In *Research and Applications in Structural Engineering, Mechanics and Computation - Proceedings of the 5th International Conference on Structural Engineering, Mechanics and Computation*, Zingoni, A. (Ed.), 1503-1506, Taylor & Francis Group, London, 2013.