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High pressure dissipative granular materials for earthquake protection of houses

Visokotlačni granulirani disipativni materiali za protipotresno zaščito hiš

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Abstract: In the recent years different types of dampers for structural control in civil engineering have been developed, where one of the most promising solutions are viscoelastic dampers. In this paper we demonstrate that by utilizing knowledge on the effect of inherent hydrostatic pressure on the time- and frequency-dependent behavior of polymers it is possible to design and build the ultimate insulation systems for civil engineering applications. An optimal solution is achieved by using highly pressurized multimodal granular polymeric materials. The results on case material, Thermoplastic Polyurethane, showed that by increasing inherent pressure of the material from 1 bar to 2000 bar the frequency at which material exhibits its maximal damping properties was shifted from 37 kHz, at P=1 bar to 235 Hz at P=2000 bar. At the same time, the increase of inherent hydrostatic pressure from 1 bar to 2000 bar changes material stiffness up to 2.5 times, while the damping properties increase up to 5.2 times.

Key words: Dissipative granular materials, Viscoelasticity, Earthquake protection, Pressure, Thermoplastic Polyurethane.

Povzetek: V zadnjih letih so bili razviti različni dušilni elementi namenjeni nadzoru struktur v gradbeništvu, kjer eno izmed najbolj obetavnih rešitvah predstavljajo viskoelastični dušilni elementi. V tem prispevku bomo pokazali, da je z uporabo znanja o vplivu inherentnega hidrostatičnega tlaka na časovno in frekvenčno odvisno vedenja polimerov mogoče načrtovati in zgraditi ultimativni izolacijski sistem za uporabo v gradbeništvu. Optimalna rešitev je dosežena z uporabo multimodalnega granuliranega polimernega materiala pod visokim tlakom. Rezultati, na primeru TPU pokažejo, da se z večanjem inherentnega tlaka materiala, iz 1 bar do 2000 bar pomakne frekvenca, pri kateri material izkazuje svoje maksimalno dušenje iz 37 kHz, pri P = 1 bar do 235 Hz pri P = 2000 bar. Hkrati, povečanje inherentnega hidrostatičnega tlaka iz 1 bar do 2000 bar spremeni togost materiala do 2,5-krat, medtem ko so dušilne lastnosti povečajo do 5,2-krat.

Ključne besede: Disipativni granulirani materiali, Viskoelastičnost, Protipotresna zaščita, Tlak, Termoplastični Poliuretan.

1. Introduction

In the last decades the base isolation of structural systems and structural components became increasingly developed and applied in order to mitigate the earthquake damaging impact. The idea itself is relatively simple and has not been invented by scientists and engineers in the last century. The archaeological investigations prove that in ancient civilizations the idea of base isolating of important buildings has been already applied. The ancient Chinese used to place a deformable layer between the ground and house foundations thousands years ago [1]. Today it is generally believed that the oldest known and still existing base isolated structure is the tomb of Cyrus the Great (559-530 B.C.) in Pasargadae, Iran, Fig. 1.

Figure 1. The tomb of Cyrus the Great (559-530 B.CX.) in Pasargadae.

Its construction started in 546 B.C. The attempts of ancient builders were governed by the challenges of construction monumental buildings in the area with the high seismic hazard, Fig. 2.

In the modern era, the simple isolation was for the first time considered as the seismic design strategy by the Italian government after the Messina earthquake in 1908. There were 160,000 casualties due to collapse of unreinforced masonry buildings. In 1909, J.A. Calantarients [2] submitted an application to the British patent office. He proposed a system, named as "free joint", where the building is set atop of the layer of fine sand, mica or talc that would allow it to slide during an earthquake. As an alternative he also proposed placement of rollers to the baseband.

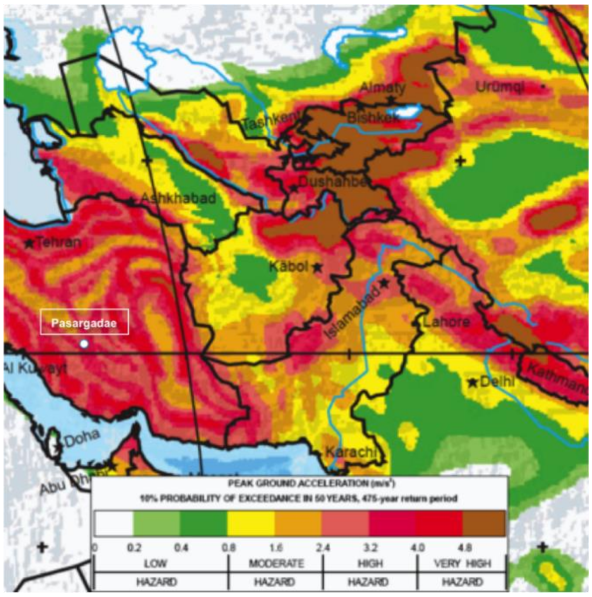

Figure 2. Seismic hazard map of Central Asia with approximate location of Pasargadae.

The first known base isolated multistory building in Europe is the so-called "Skyscraper" that has been erected in Ljubljana, Slovenia in the year 1933. Twelve-story reinforced concrete frame structure, with masonry infill walls, was the tallest building (70m) in Middle Europe at the time of its construction. Foundation belts of this building are separated from the deep pile foundation system by the multilayered sandwich composed of zinc, asphalt, bitumen and lead.

In 1965, the first unreinforced-rubber (bearings made of rubber not containing reinforcing steel plates) base isolated structure in the world, i.e., the Pestalozzi primary school building, was constructed in Skopje, Macedonia. After 40 years the old bearings were replaced by the new, more sophisticated ones. However, the results of investigation proved that the old isolation was still functional [3].

The first base isolated building in the USA, the Foothill Communities Law and Justice Center in the County of San Bernardino, California, has been built in 1985 where high-damping natural rubber was used for its bearings. Further development of base isolation systems introduced slider/elastomer combination that was applied in the Mackay School of Mines at the University of Nevada in the USA in 1992. It was the first case of base isolation introduction in rehabilitation of existing buildings. The innovation was in introduction of such a type of base isolation, where sliders create a system with a long period, while the elastomeric bearings control displacements, torsion, and can produce a stiffening action if the displacement becomes large.

In Japan, the first large base-isolated building was constructed in 1986. After that, within ten years, more than 550 base-isolated buildings were completed. During the first years the most commonly used systems were based on natural rubber bearings with mechanical dampers or lead-rubber bearings. Recently, the use of high damping natural rubber isolators is increasing. The additional impulse to introduction of base isolators, and the underlying research was triggered by Kobe earthquake in 1995.

Current development of base isolating systems is intensively supported by extensive theoretical and experimental investigations, both in laboratories and on-site. The recent development of new isolating products and prediction computational tools is supported by the large-scale laboratory facilities – shaking platforms and pseudo-dynamic systems. There are two main directions of isolator development [4]:

- Base isolation bearings are used to modify the transmission of the forces from the ground to the building and are suitable for relatively low rising buildings, including traditional ones, where the problem of overturning is not a case;
- Passive energy dissipation includes the introduction of devices such as dampers to dissipate earthquake energy producing friction or deformation. They are suitable for high-rise buildings.

There are two main base isolating systems in use today: the slider system and the elastomeric bearing system [4, 5]. The sliding system is based on idea of total decoupling of building from the foundation. There are several problems associated with this system. In the early stage low horizontal force as those induced by strong wind can displace the structure. When a structure is displaced it will remain in this position until the next event. Over an extended period the inactivated slider may become ineffective in an earthquake. Therefore, the advantages of elastomeric bearings made them the most commonly used system for base isolation. The major benefit of elastomeric bearings is that they can be designed for higher vertical stiffness for load bearing purposes, while, maintaining lower horizontal stiffness. They also have inherent restorative forces to return the structure to its original position after the effect of an earthquake. The contemporary bearings are composed as sandwiches having layers of rubber between steel reinforcing plates.

The horizontal displacements of high-rise buildings need to be controlled due to their high flexibility and overturning possibility. Various types of dampers, which absorb a sufficient part of the earthquake-induced energy making the displacement tolerable, can serve as the displacement control devices [4, 5]. They are also suitable for retrofitting of existing buildings, especially if the application is external or does not interfere with the occupants.

Different types of dampers have been developed in recent decades [6]:

- hysteresis dampers that utilize the deformation of metal parts;
- visco-elastic dampers based on stretching of an elastomer in combination with metal parts;
- fricative dampers that use metal or other surfaces in friction;
- viscous dampers that compress a fluid in a piston-like device;
- hybrid dampers that utilize the combination of elastomeric and metal or other parts.

As stated in Eurocode 8, Part 1 [7], the reduction of the seismic response may be achieved by increased damping or by modifying the shape of the fundamental mode (or by combination of both). It is our believe that currently used systems, that are based on the use of polymeric materials (visco-elastic based dampers), can be even further optimized as this will be shown within this paper. Understanding and utilizing the effects of hydrostatic pressure on stiffness and damping properties of time-dependent materials can have a significant effect on damping properties of materials. In the paper we will demonstrate, on the example of Thermoplastic Polyurethane (TPU), how damping properties and stiffness of material is affected by hydrostatic pressure.

The corresponding technical solution which is also presented, has been patented [8] world-wide and represents an ultimate insolation system for the earthquake protection of buildings and structures. However, it should be noted that for practical implementation of proposed damping elements, elements should be tested in order to evaluate their effectiveness as well as to identify their compliance with Eurocode standards.

2. Material properties of visco-elastic dampers

Properties of polymeric materials (thermoplastic and elastomers) are time and frequency dependent and they exhibit supreme damping properties only within a specific range of frequencies. Outside this range their damping properties are only good. Properties of polymeric materials in frequency domain are represented by two material functions:

- storage modulus G', which represents the ability of material to store energy elastically and it is related to material stiffness;

- loss modulus *G''*, which represents the ability of material to dissipate energy.

Materials used in civil engineering dampers are usually hard elastomeric and/or thermoplastic materials with high stiffness. Consequently, their damping capacity is relatively low, especially if compared to soft elastomeric materials that exhibit extremely high damping properties. The latter, however, are not used in base-insulation systems due to their low stiffness.

Fig. 3 schematically shows loss modulus (damping properties) in frequency domain for three different polymeric materials – PA6 (Polyamide 6), TPU (Thermoplastic polyurethane) and SBR (Styrene-butadiene rubber) rubber. From the figure we may learn several important facts: (i) softer polymeric materials have significantly higher damping properties, however, located at very high frequencies, i.e., in kHz and MHz range (unfortunately, they could not be used in civil engineering applications due to extremely low stiffness); (ii) if we consider frequency range (1 Hz-100 Hz) as an area of our interest we observe that none of the three materials exhibit maximum of energy dissipation in this range; (iii) damping properties of soft TPU in the frequency range of our interest is up to 300 times higher than that of PA6; (iv) the maximum damping properties of TPU and SBR are up to 2000 and 40.000 times higher than that of PA6.

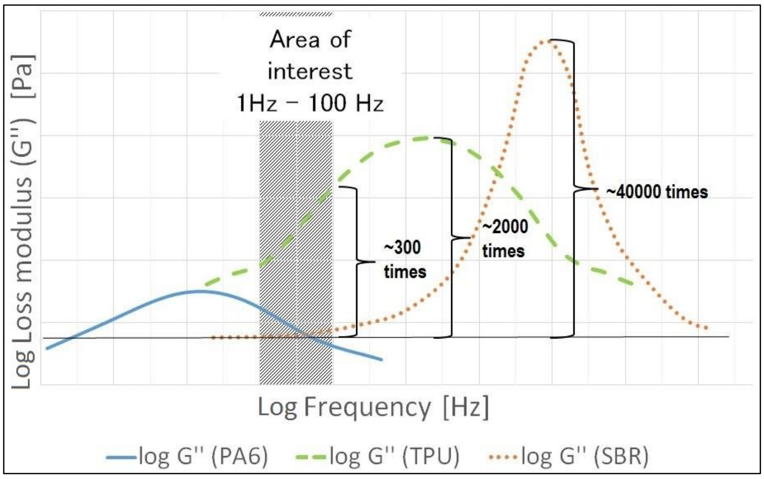

Figure 3. Loss modulus for three different polymeric materials (PA6, soft TPU and SBR).

Based on these observations we may conclude that using softer thermoplastic or elastomeric materials with higher damping capability would be beneficial in earthquake and other civil engineering applications, providing that we could shift their maximum energy dissipation peak into the frequency range of our interest, and at the same time somehow increase their stiffness. As explained further on this may be achieved by exposing viscoelastic materials to properly selected inherent hydrostatic pressure.

2.1. Effect of pressure on visco-elastic properties of polymers

It is important to emphasize that pressure can have enormous effect on the viscoelastic response of polymeric materials [9]. When we expose polymeric materials to high pressures the mobility of polymeric chains is hindered. On the macro scale this is exhibited through the extension of the material creep and relaxation time scales [10]. Hence, under hydrostatic pressure the viscosities and viscoelastic relaxation and retardation times of polymers increase.

Stress relaxation is the process, in which a polymer relaxes after application of a sudden deformation, i.e., torsional shear deformation. Whereas, for the case of shear creep a polymer has to be exposed to a sudden shear stress, which then initiates the creep process. Deformation or stress load should be applied at particular boundary conditions, i.e., temperature and pressure, such so the material response is measured at these equilibrium conditions. Relaxation and creep of polymers are slow processes and they may last over many decades in time, thus, experimentally it is almost impossible to measure a complete ('long-term') relaxation or creep curve. Therefore, it is a common practice to determine the relaxation modulus or creep compliance within a certain range of time called the Experimental Window (EW). Once individual segments are measured at different temperatures and/or pressures, a mastercurve can be generated using time-temperature *(t-T)* or, equivalently, time-pressure *(t-P)* superposition principle (SP). Different segments determined at different temperatures and at constant pressure are shifted by factor Log a_T, and segments measured at different pressures and at constant temperature are shifted by factor Log a_P, so the corresponding mastercurves can be generated [10, 11]. In Fig. 4 this is demonstrated for the case of creep measurements at constant temperature and different constant pressures.

Considering this, one may observe results at different reference temperatures or pressures, where mastercurve is appropriately shifted along the time axis. In the case of pressures, higher pressure shifts master curve to the longer times (maser curve is shifted to the right). The effect is opposite in frequency domain, where mastercurve at higher pressures is shifted to lower frequencies (maser curve is shifted to the left).

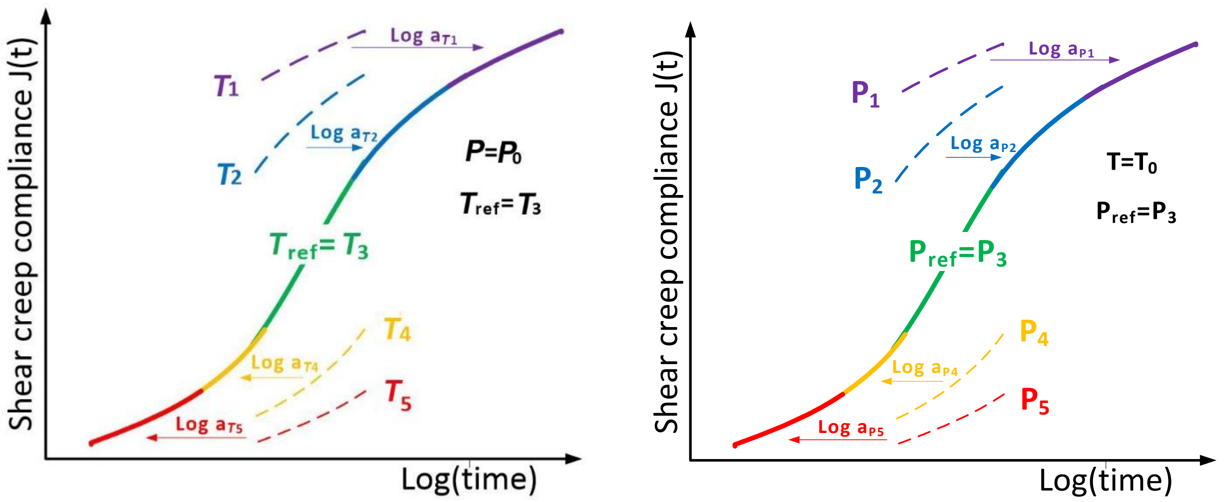

Figure 4. Generation of creep mastercurve using *t-T* SP at constant pressure (left), where $T_1 > T_2 > T_3 > T_4 > T_5$ and *t-P* SP at constant temperature (right), where $P_1 < P_2 < P_3 < P_4 < P_5$.

It is also important to mention that frequency dependent material functions may be obtained from those measured in time-domain through the interconversion. Within the framework of the linear theory of viscoelasticity, static and dynamic material functions are interrelated in the Laplace space [11].

Within the framework of this paper we show that by proper selection of the type of the material and proper selection of the hydrostatic pressure one can shift the maximum of the material damping properties to the frequency range of our interest. By doing this energy absorption properties of a damper could be increased several orders of magnitude. In the case of soft materials this would mean that stiffness of material is increased and at the same time damping capabilities of polymeric material is fully utilized. We demonstrate the ability to shift properties of polymeric materials via storage modulus, *G'(ω)*, and loss modulus *G''(ω)* measured at different pressures. Material functions in frequency domain were obtained through the process of interconverison from the shear relaxation modulus, *G(t,T,P)* measured on a specially designed apparatus known as CEM Measuring System – CMS [12, 13].

3. Experimental setup

The CMS apparatus [10, 12, 13] was developed to study the combined effects of temperature and hydrostatic pressure on behavior of polymers. The system can measure the volume and the shear relaxation moduli of solid polymer specimens simultaneously subjected to temperatures from -40°C to +120°C and pressures from atmospheric to 500 MPa [12, 13]. CMS apparatus consists of four main parts: hydraulic system, thermal system, data acquisition system and measuring inserts.

Hydraulic system includes hand pump for pressurizing silicone fluid to a pressure vessel. In thermal system, a circulator and thermal bath are used to regulate temperature of specimen. In order to process and record the signals from measuring inserts, i.e., relaxometer and dilatometer, data acquisition system is used which combines a carrier amplifier and computer. The CMS apparatus assembly is shown in Fig 5.

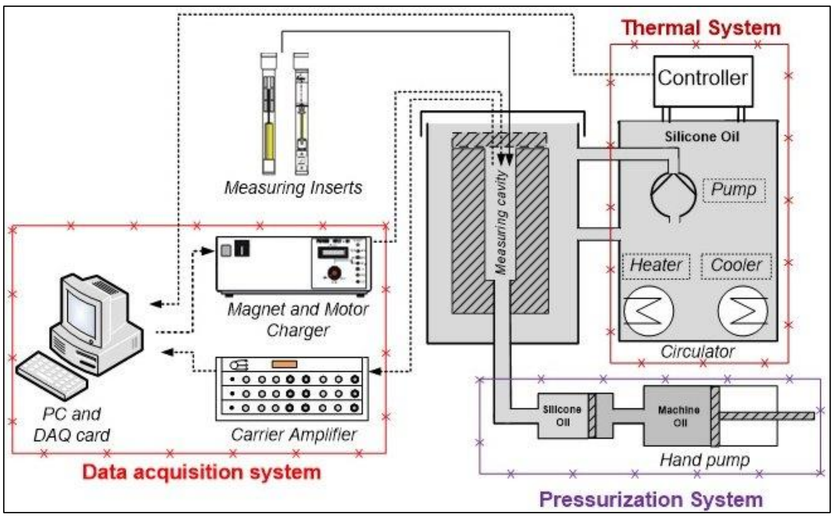

Figure 5: Schematic of CMS apparatus [12, 13].

3.1. Measuring principle

CEM Measuring System measures four physical quantities: temperature, *T(t)*, pressure, *P(t)*, specimen length, *L(t,T,P)*, and the decaying torque, *M(t,T,P)*, resulting from the initially applied torsional deformation, θ_0, on the sample. Using these quantities measured at constant or varying temperature and pressure, other material functions can be calculated [12, 13]. In this particular case shear relaxation modulus is of our interest and is determined by measuring the decaying moment of a specimen exposed to selected constant temperature and pressure boundary conditions. The relaxation modulus curve usually extends over many decades of time, which are practically not possible to characterize at constant temperature or pressure. Keeping this in mind, experiments are performed within a certain time-interval – experimental window. A set of different shear relaxation modulus segments is obtained when experiments are carried out at different temperatures, and/or pressures. The segments are then shifted along the logarithmic time scale to produce master curves using the time-temperature t-T and time-pressure *t-P* superposition principles [11]. The final master curves represent the long-term behavior of the material, at the chosen reference conditions. The mastercurves of storage *G'(ω)* and loss modulus *G''(ω)* in frequency domain were then obtained from *G(t, T, P)* through the interconversion [9, 10].

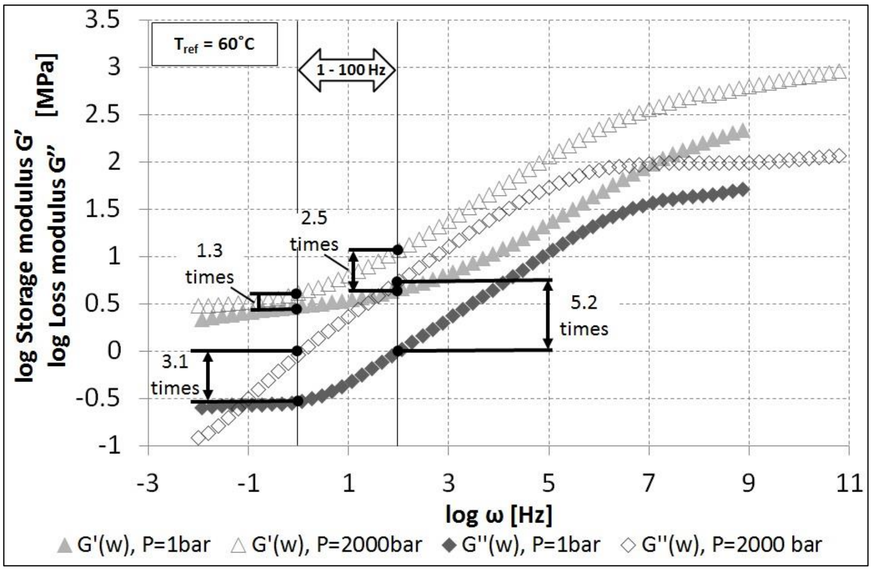

Figure 6. Storage *G'* and loss modulus *G''* at *P* = 1 bar and *P* = 2000 bar.

4. Results

For clarity reasons we will examine only one type of material, i.e., soft TPU, delivered by BASF company. For the same reason the results on storage *G'(ω)* and loss modulus *G''(ω)* are shown for two pressures, i.e., 1 bar and 2000 bar, only. The full symbols represent measurements done at lower pressure (*P* = 1 bar), whereas the empty symbols represent measurements done at higher pressure (*P* = 2000 bar). The results are shown in Fig. 6.

Considering the fact that we are interested in low frequency range, i.e., between 1 Hz and 100 Hz, we will examine the effect of pressure on stiffness and damping properties of TPU within this frequency window.

From Fig. 6 we may clearly see that within the region of our interest (1 – 100 Hz), changes of inherent (hydrostatic) pressure of TPU from 1bar to 2000 bar cause material properties change for several orders of magnitude. Specifically, at frequency 1 Hz and pressure 1bar the storage modulus (representing stiffness) is *G'*(*ω* = 1 Hz, *P* = 1bar) = 2.99 MPa, whereas at pressure 2000 bar the storage modulus increases to *G'*(*ω* = 1 Hz, *P* = 2000 bar) = 4.07 MPa. Hence, material becomes 1.4 times stiffer. At the same frequency of 1Hz the loss modulus (representing material damping characteristics) at pressure 1 bar is *G''*(*ω* = 1 Hz, *P* = 1 bar) = 0.29 MPa, whereas at pressure 2000 bar it rises to *G''*(*ω* = 1 Hz, *P* = 2000 bar) = 0.92 MPa. This means that at elevated pressure the materials ability to dissipate energy increases 3.15 times.

For the higher end of the frequency window, i.e., *ω*= 100 Hz, we observe analogous trends. At 1 bar the storage modulus is *G'*(*ω* = 100 Hz, *P* = 1 bar) = 4.55 MPa, whereas at the pressure *P* = 2000bar the storage modulus becomes *G'*(*ω* = 100 Hz, *P* = 2000 bar) = 11.55 MPa, meaning that material stiffness is increased 2.54 times. At the same time the loss modulus at pressure 1 bar is *G''* (*ω* = 100 Hz, *P* = 1 bar) = 1.04 MPa and at pressure 2000 bar it becomes *G''*(*ω* = 100 Hz, *P* = 2000 bar) = 5.42 MPa. Thus, the material ability to dissipate energy has increased 5.19 times.

From Fig. 6 one may easily see that by further increasing material inherent pressure we may increase the stiffness and damping properties of TPU up to 100 times!

It is worth mentioning that for some special materials this increase may go up to 104 times!!!

Using the time-pressure *(t-P)* superposition principle we can predict how frequency, at which TPU exhibit maximum damping properties (maximal value of loss modulus *G''(ω)*) changes with pressure.

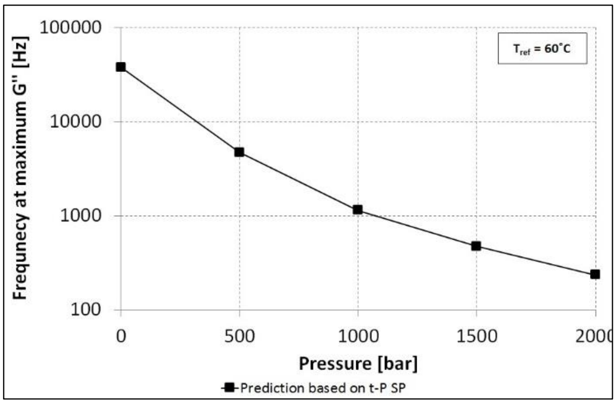

Figure 7. Frequency at maximum damping.

Fig. 7 shows frequencies at which loss modulus has maximal values in dependence on pressure (from 1 bar to 2000 bar).

We can see that higher pressure shifts maximal values of damping (maximal values of loss modulus *G''*) to lower frequencies. For example, frequency at which maximal value of damping at pressure P=1bar occurs is around ω = 37 kHz, whereas at pressure P = 2000 bar it moves to as low as ω = 235 Hz.

5. Highly pressurized damping elements for optimal structural and vibration control

Based on the presented results, where we showed that existing solutions for structural and vibration control do not and cannot fully utilize damping characteristics of time- and frequency-dependent materials, we developed the ultimate base insulation system, which we have called DGM System (DGM – Dissipative Granular Materials).

As we have showed, the inherent (hydrostatic) pressure changes frequency dependence of polymeric materials. Hence, by proper selection of damping material and a pressure to which material is exposed one can match the frequency range of its maximum damping properties with the resonance frequency of the building and/or structure exposed to earthquakes. In this way we fully utilize damping characteristics of the selected material and maximize the energy absorption properties of the damper.

Using this unique property of polymeric materials enabled us to design and build ultimate adaptive damping elements. For doing this we have additionally utilized patented finding that viscoelastic granular materials with properly selected multimodal size-distribution exhibit fluid-like behavior, while maintaining behavior of the bulk material from which they were made. Hence, they may be used as "pressurizing media" to impose inherent hydrostatic pressure on itself and consequently change its own damping properties. Such patented damping elements consist of elastomeric granular material, which is encapsulated in a glass, basalt or carbon fiber tube, as shown in Fig. 8.

This design enables us to pressurize the granular material inside the damping element. At higher pressures properties of material shift to lower frequencies, compared to the reference values.

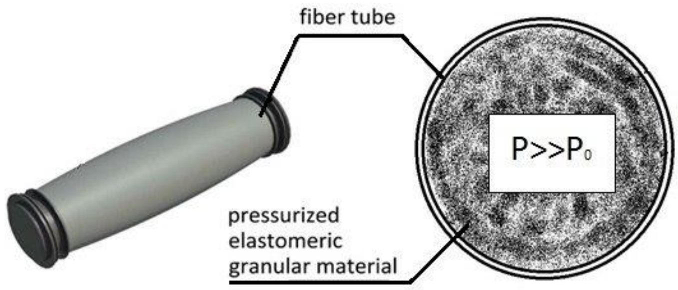

Figure 8. Damping elements consisting of pressurized elastomeric granular material encapsulated by fiber tube.

Working principle of such damping element is explained in the diagram in Fig. 9, which shows the original dynamic response of the excited structure caused by earthquake and reduced dynamic response of the excited structure when damping elements are applied. The solid line on the right schematically shows damping characteristics of the selected granular viscoelastic material at atmospheric pressure. By self-pressurizing elastomeric granular material to properly selected hydrostatic pressure its frequency characteristic may be adjusted as required, to match the resonance frequency of the structure. This is schematically shown with an arrow showing that line in the right-hand side of Fig. 9 changes its frequency position to the dashed line. By modifying hydrostatic pressure to which elastomeric nano-sized granular material is exposed we can adjust the frequency, at which material exhibits maximum energy absorption, such so to match the frequency of the vibrating structure. By doing so, we observe substantial reduction of vibration amplitudes.

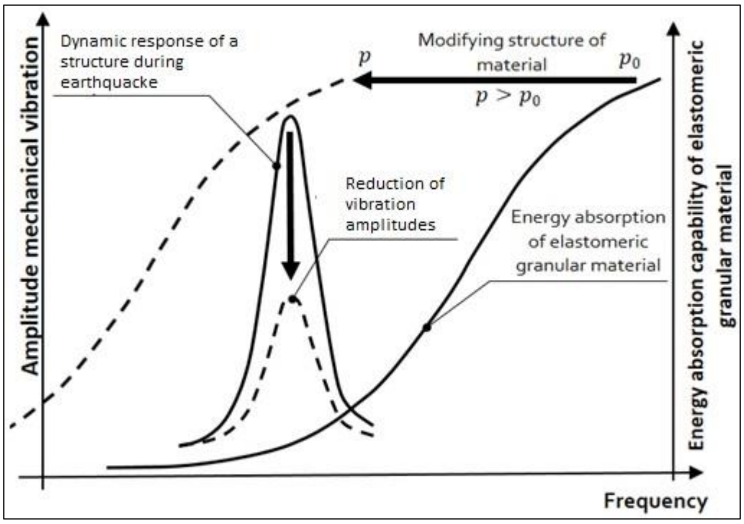

Figure 9. Schematic presentation of working principle.

6. Discussion and conclusions

Within the paper different types of dampers for structural control in civil engineering have been mentioned, where one of the most promising solutions are viscoelastic dampers. Using the unique property of polymeric materials - with increased hydrostatic pressure its damping properties increase tremendously, enabled us to design and build ultimate adaptive damping elements, which could replace rubber base insulation used in current earthquake protection engineering.

In this paper we have demonstrated that by utilizing the basic knowledge on the effect of inherent hydrostatic pressure on the time- and frequency-dependent behavior of polymers it is possible to match the frequency of maximal damping of polymeric material with the frequency which occurs in vibrating system.

In this process we utilized an apparatus that allows determination of material functions, as functions of pressure and temperature in time or frequency domain, e.g., *G(t)*. Presented CEM Measuring System is an example of such apparatus.

For the selected TPU material we found:

- By increasing pressure from 1 bar to 2000 bar the frequency at which material exhibits its maximal damping properties was shifted from 37kHz, at P = 1bar to 235 Hz at P = 2000 bar.
- The increase of inherent hydrostatic pressure from 1 bar to 2000 bar changes values of storage modulus G' up to 2.5 times (depending on the frequency), while the values of loss modulus G'' are changed up to 5.2 times.

Correlation between pressure in damping elements and the effect on the structure and response of the whole system is a matter of further investigation.

Acknowledgements

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