The new concept of steel structure bracing

R. Fojtík, T. Novotný

***Abstract*—**The design of high rise vertical structures that must withstand the actions of horizontal forces consisting primarily of wind actions, earthquake actions etc. puts greater demands on the structure reinforcement resisting to these forces. The structures concerned include masts, towers and high-rise buildings. Many different systems are used as vertical bracing. One of them is a new stiffening system called "circular reinforcing system" presented in this paper. Because it is the new structural system it is now subject to experimental tests to proof its sufficient stiffness and other properties for practical applications.

***Keywords*—**Bracing, steel, high-rise buildings, towers, seismicity.

I. Introduction

Since the origins of the very first buildings, there have always been efforts to build constructions, especially of religious importance, Home Insurance, 1885, New York) [1]. These buildings did not have significant problems with horizontal forces since the ratio of height to width was close to 1:1 and also the wall system provided sufficient horizontal stiffness. Due to great weight and relatively low solidity it was impossible to exceed the height limit. With the use of new materials for building slim and high-rise constructions such as reinforced concrete and steel, which made it possible to build relatively light and slim skeletal constructions, the demand for higher requirements as for constructional reinforcement, so-called ´height tax´, grew together with the growing height. Since the first sky-scrapers until now countless high-rise buildings have been constructed using new materials and, above all, construction systems. Nearly every high-rise building which strives to surpass the up to now giants comes up with a new construction solution.

The leap from the first sky-scraper to the last one is almost 780 m. One of the most important elements of the construction system is the reinforcement ensuring the stability of such constructions.

This work was supported in part by of the Ministry of Education, specific university Student Research Grant Competition of the Technical University of Ostrava under identification number SP2014/180.

Roman Fojtík, VSB - Technical University of Ostrava, Faculty of Civil Engineering, 708 33 Ostrava, Czech Republic (corresponding author to provide phone: +420 597 321 398; e-mail: roman.fojtík@vsb.cz).

Tomáš Novotný, VSB - Technical University of Ostrava, Faculty of Civil Engineering, 708 33 Ostrava, Czech Republic (corresponding author to provide phone: +420 597 321 398; e-mail: tomas.novotny@vsb.cz).

II. Overview of reinforcing systems

Multi-storey buildings of regular proportions use mainly two basic types of vertical reinforcing systems.

The first type is represented by truss stiffeners, which are built in various modifications. Generally, they are to be ´drawn diagonals´, the advantage of which is a subtle profile. However, bigger vertical deformations occur due to small connecting-rod surface.

Another alternative to truss stiffeners is the transmission of pressure forces, which requires an increase in the profile cross-section of diagonals due to great bracing.

Next types are frame stiffeners formed by stiff frame connections transmitting axial forces as well as significant bending moments. This type of stiffening is limited by the stiffness and labour-intensity of contact points.

The described vertical stiffening systems can be used for constructions of 30 to 40 storeys with the ratio of height to width not exceeding 6:1. For constructions up to 60 storeys, it is moreover necessary to insert reinforcing strips formed by additional stiffeners, which are found all along the height and width of a storey so that even the vertical columns of a construction would be involved. Constructions exceeding 60 storeys usually use the so-called ´tubular system´, which was developed in the USA.

The basic principle of the tubular system is to create a very stiff constructional circumference with a free inner space. This system can be used as a ´frame´ (framed tubes) using dense depositing of façade poles mutually connected by rungs with frame connections. The ´World Trade Centre´ was an example of this technology used. Another type of tubular system is ´truss tubular system´ (braced tubes). One of the most famous used truss reinforcements is ´truss mega construction´ formed by truss diagonals of big profiles running through several storeys. A big advantage of this system is, apart from others, also the transmission of vertical forces. A representative using this system is ´J. Hancock Center´. Another modification of the tubular system are ´bundled tubes´, which use the previously mentioned systems in a bundle of individual tubes mutually interconnected. The highest representative is ´Burj Khalifa´with its height of 828 m.

A. Load and statics

All vertical slim constructions are in addition to a regular vertical load such as their own weight, utility load, snow load, etc. also exposed to significant, especially horizontal, forces of wind, earthquakes, imperfections and others.

Wind strongly influences slim high constructions above the surrounding terrain and buildings. The first actual frequency of slim constructions is very often lower than 4 Hz, sometimes even 1 Hz, which means that it is necessary to consider the dynamic effects of wind and seismicity.

Earthquakes in the Czech Republic are relatively insignificant compared with seismically active areas in the world. Nevertheless, according to ČSN EN 1998 there are areas of low and higher seismic activity in the Czech Republic, characterized by the value of proposition acceleration higher than 0,04 g [2], [3]. In such areas, e.g. the areas of Cheb or Ostrava, it is necessary to consider this type of load as well.

Imperfection expresses the influence of the deflection of a construction from its vertical position on the inner forces. These unfavourable impacts increase together with the height and weight of the vertical load. Other unfavourable impacts are: the influence of shortening poles from the vertical load, interaction with bedrock (overturning), and thermal expansivity of constructions.

III. New circular bracing system

The basic requirements for a bracing system arise from its function and location in a construction. The purpose of this bracing system is to transmit horizontal forces of wind, earthquakes and imperfections. Apart from the transmission of horizontal forces, which are transmitted by all bracing systems, the new hoop-shaped stiffener makes it possible to transmit also the vertical load, such as the own weight of a construction, utility load, etc. With the implementation of the hoop-shaped system as a stiffener into the tubular system of high-rise buildings, we get minimal stiffener construction surface, which otherwise makes the view from a building impossible. The last and the most important property of the stiffener are its favourable static and dynamic characteristics. A hoop being a curved and closed element (ideally a circle), easily transmits great pressure forces, supposing the hoop is stable, which is ensured by connecting rods anchored in the centre of the hoop [4]. The dynamic properties of the particular hoop stiffeners can be modified to certain extend by prestressing the individual stiffeners.

A. *Circular stiffener development procedures*

At the very beginning it was necessary to choose the right hoop profile, which is strained by great axial pressure. Ideal cross-sections are e.g. closed profiles (tubes, angular tubes) or open, flatwise placed U-profiles and HEA-profiles. Next, the optimal number of prestressed rods was determined. Using numerical models, the most suitable options for the location and number of rods were searched. The aim was to find a balanced ratio of construction utilization to its weight. In total, 6 different numerical hoop stiffeners were made. The particular models differed in the number of connecting rods. The numerical models where the size of the stiffener in the frame was 10 x 10 m were loaded with vertical and horizontal forces equal to a building of 70 m with the ground plan of an equilateral triangle with a side length of 10 m.

The first numerical model contained 40 connecting rods (see Fig. 1a). This version was characterized by minimal requirements for the hoop stiffness caused by a great amount of connecting rods, which divided the hoop into short sections.

This model was also characterized by great stiffness and weight of prestressed elements. Next numerical models were hoops with 16, 14, and 12 connecting rods (see Fig. 1b, c), whose ratio of stiffness to weight was close to the requirements.

The above mentioned variants showed the optimal ratio of hoop utilization and connecting rods, therefore, the choice of the most suitable stiffener construction will depend on the size of the stiffening hoop and load. The last variant using the same hoop as the previous models is a variant with 8 connecting rods (see Fig. 1d), which shows increased requirements as for the hoop stiffness.

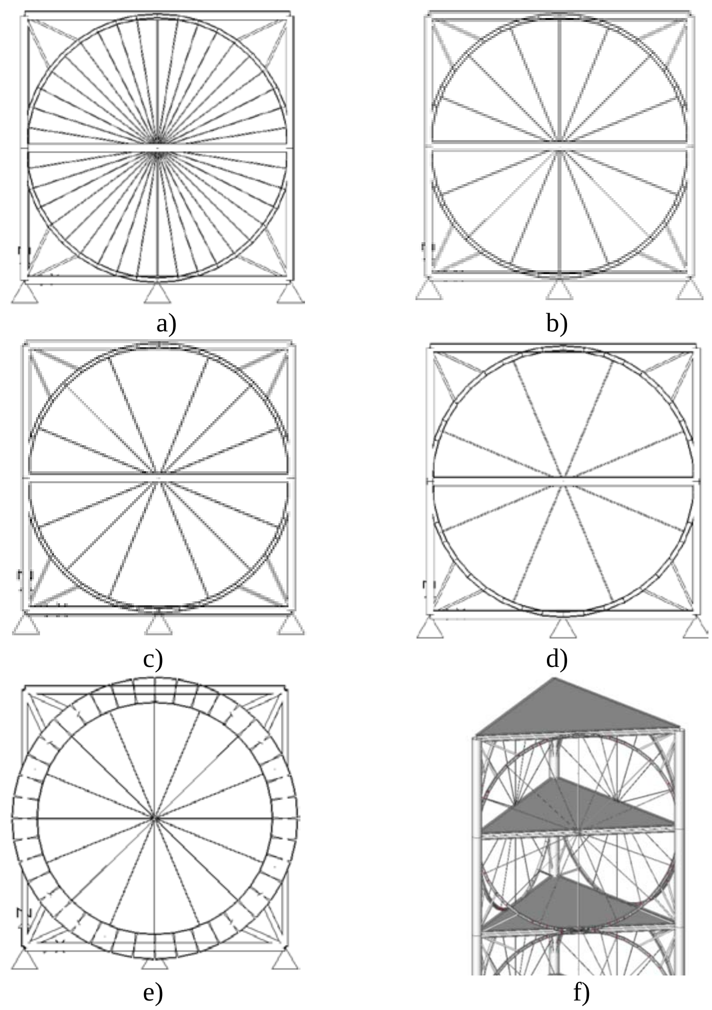

Fig. 1 Hoop wall stiffeners draft schemes a) 40 connecting rods, b) 16 connecting rods, c) 12 connecting rods, d) 8 connecting rods, e) HEA 1000 hoop, f) Stiffener placement construction scheme.

This causes an increase in weight of the overall hoop system. A variant deviating from the above mentioned line was designed from a HEA 1000 profile (see Fig. 1e), which was to replace the function of circumference posts. This variant is absolutely unsuitable for its extreme weight. The prestressed connecting rods do not function appropriately due to great stiffness of the hoop itself.

All of the above mentioned models were created for the purpose of finding the basic construction geometry, optimal profiles and getting an idea of how constructions behave. All the stated numerical models were created in the SCIA Engineer program. Having compared all the variants [4], the variant of a circular stiffener with 16 connecting rods was chosen.

B. Figures and Tables

A scale numerical model (see Fig. 2) was created in the ratio 1:1 with experimental samples using the SCIA Engineer program [5]. First of all, linear calculations, which showed favourable construction effect, were carried out.

Rod elements with a non-linear attribute ´of only tensile strain (physical non-linearity) ´ and also the sheet hoop board element (Kirchhoff´s theory) were used for the construction of this scale numerical model.

The load was done by point forces inferring construction slide strain corresponding with the real laboratory strain. Timoshenko´s method of solving geometrical non-linearities was chosen for the calculation of the numerical model. This method is used with geometrically non-linear constructions, whose deformations are relatively small. The reason for choosing the method was also the constant force under strain, which due to the low weight of the tested sample and great force corresponds with the planned experiments.

Current results from the experimental measurements are not in accordance with the numerical models and that is why a non-linear connection between the hoop and the stringing,

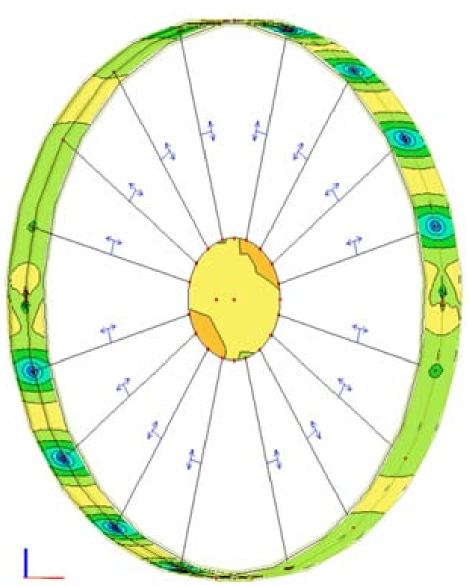

Fig. 2 Numerical model of the experimental sample (SCIA Engineer)

which directly describes the real behaviour of the point under strain, was chosen for new numerical models. The data was acquired from an experiment (see Fig. 3) [6].

Fig. 3 Bursting test rod

This function described the results of the numerical model for the behaviour of experimental samples without prestress while under strain. Unfortunately, this function cannot be successfully used at modeling prestress. If prestress forces are involved in the model, the connecting rod gets stretched but the prestress force is lost, which does not correspond with real behaviour, where the prestressed profile keeps its tautness. Only further numerical models will show if it is possible to model this situation using the commonly available and commercially used software SCIA Engineer.

C. Requirements for experimental measuring

There are many requirements for the creation of experimental samples. The suggested scale models should be made in a way so that the stiffness of the particular elements would proportionally describe the stiffness of a real construction as closely as possible. The profile and material of the hoop and connecting rods should correspond with the requirements listed in chapter 3. The choice of the scale models design production should include especially a suitable cross-section and material so that the equilibrium of the stiffness of the hoop and rods was more or less proportional. For instance, if the rods were too stiff, the hoop would be destroyed. On the other hand, if the rods were less stiff, they would be damaged and consequently the whole system would be destroyed. A suitable profile must be able to transfer the maximum tensile forces which correspond with a required load. The samples must be designed also in a way so that they the dimension and stiffness can be adapted to the facilities of a laboratory. The first step to verify the functionality of the reinforcing system is shear resistance. For the stress test, a hydraulic press was used, which basically cannot carry out the shear endurance tests of wall elements and constructions.

In order to be able to carry out shear endurance tests on the tested samples, it was necessary to create auxiliary retaining devices (see Fig. 4), which make shear tests while using a hydraulic press possible.

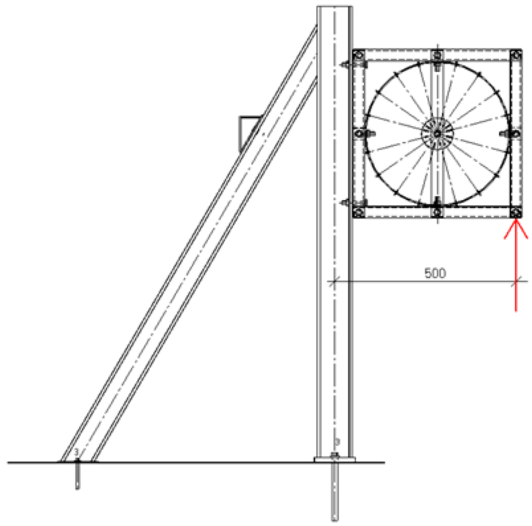

Fig. 4 Retaining construction scheme

An auxiliary construction consists of two parts. The first one is an anchor frame which works as a retaining construction against the pressure forces coming from the hydraulic press. The forces which the anchor frame can resist without any deformations and without influencing the result correspond with the load of 60 kN on the console of 50 cm in length. Another part of the auxiliary construction facilitating the shear tests of the tested samples is a swinging frame, the function of which is to enable mobility of the retaining construction in the direction of the stiffener and suitable stiffness in a vertical direction to the flat surface of the tested sample.

During the experimental verification of the hoop stiffener functionality the ČSN EN 1990 norm recommendations were followed [7]. The project of new constructions should be a combination of tests and calculations, where the tests can be carried out for the following reasons:

- if there are not any suitable computational models
- if it is necessary to use a great deal of similar parts
- to confirm the suggested data of a project by a check test

Based on the above stated reasons, the experimental tests were carried out respecting all three reasons for doing tests.

The experimental tests themselves were carried out based on ČSN 732030, which offers a guideline to experimental tests. To be able to get a plastic echo of the tested samples as well, the burdening was done gradually.

D. The first series of experimental samples

N In order to verify the simplified numerical models two stages were chosen. The first stage is characterized by no rod prestress and the second stage should use the advantage of ideal parameters of sample stiffness caused by prestress force of 2,000 N, which was injected to all the rods of the tested samples. Despite the primary requirement of equal stiffness in both the main directions of the stiffener hoop, which ideally corresponded with the " jäckl" profile, the profile of skelp 50/5 was chosen after all. The reason for choosing this option was especially great stiffness of the " jäckl" profile but also the inconvenience of the profile for seaming in a small radius. Both the parameters are ensured by a skelp hoop, the only disadvantage of which is different stiffness in the direction of the main axis, which was necessary because of small stiffness in the direction of the hoop´s level and a relatively great amount of surface to be able to create a bolted connection so as not to weaken significantly the hoop in the place of connection. Also, the profile and material of the rods must be chosen so that their parameters fulfil the requirements of experimental measuring. As a suitable profile, a square-shaped cross-section of a steel rod with the side length of 5 mm was chosen. The profile of the square was chosen due to suitable surface for sticking strain sensors on. Their fitting on cylinder surface of small radius is not suitable.

The static shear endurance test was carried out on a scale model (1/20) of a real circular stiffener construction.

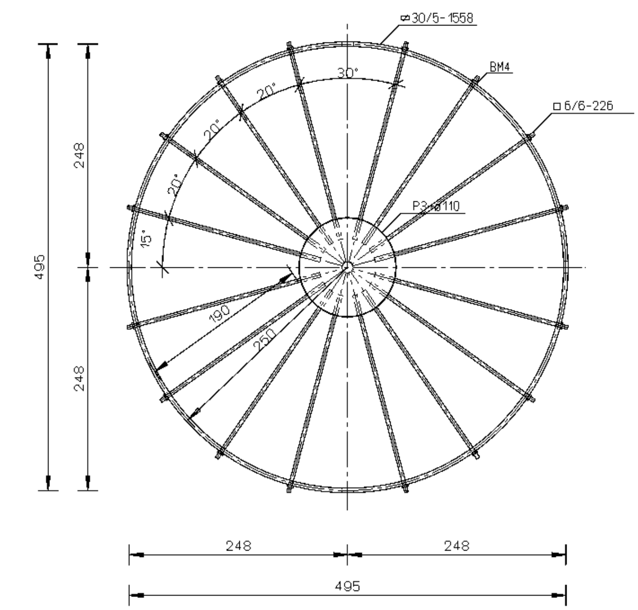

Fig. 5 Experimental sample construction scheme

The construction of a stiffener scale model consists of a skelp hoop S235 of a rectangular profile 30/5. The stringing consists of 16 square-shaped rods of 5/5 profiles. At the end of the rods are threads of Ø 4 mm, by means of which prestress will be injected into the matrix. The rods are welded on to the central sheet metal of circular shape. The diameter of the sheet is 110 mm and its thickness is 3 mm. All the parts of the scale model of the hoop stiffener are made of steel S235 (see Fig. 5).

The aim of the stress tests is to verify the functionaly of the circular stiffener. Several measuring technologies and procedures were used to do this. For the stress tests of ULS parts the record from the hydraulic press about the shift of the jaw and the amount of strength was used [8]. The verticality of the swinging frame was verified by a track sensor during the test and the change in stress in certain chosen points was monitored by strain sensors. As a complementary check method, photogrammetry was chosen. Its results can be used to verify the recorded data.

Fig. 6 Advertising hoarding planned construction visualization

The recorded data of the experimental measuring is compared with an SLS model in order to find an optimal SLS model, which could, if in concordance, substitute difficult, demanding and costly experiments. The concordance of the real and virtual models is burdened by many inaccuracies on both sides. These are caused especially by inaccuracies during the production of samples on the one hand, and on the other hand by an idealized model.

The tested model without initial prestress showed its specific behaviour. What is charecteristic of the samples without prestress is mainly the diagonal influence of the stiffener without the rods placed directly on the stress axis being involved. The set of these experimental samples consists of three identical samples, which do not contain any prestress.

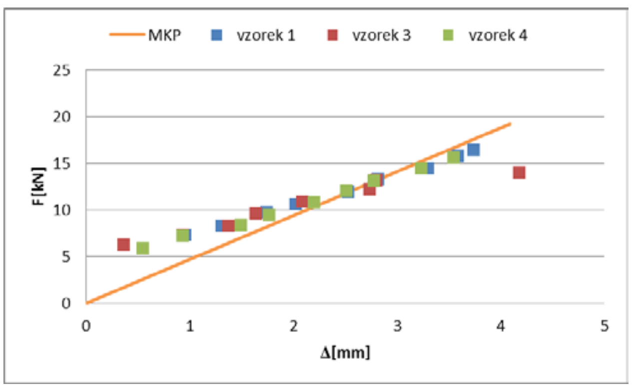

Fig. 7 The comparison of experimental samples without prestress with an MKP model

The concordance of the FEM model with the experiments is almost ideal in the interval of 2-3 mm. The differences in the interval of 0-2 mm are caused especially by shaping up the experimental samples (slackness in connections) during the load start. The interval of 3-4 mm is influenced by a gradual damage of bolted connections due to the thread activity.

IV. Conclusion

The hoop bracing system is a concept of untraditional vertical constructions stiffening approach bringing favourable properties such as: ´the use of steel in traction and simple pressure, reducible stiffness, relatively low weight, adjustable decline and also unconventional design´.

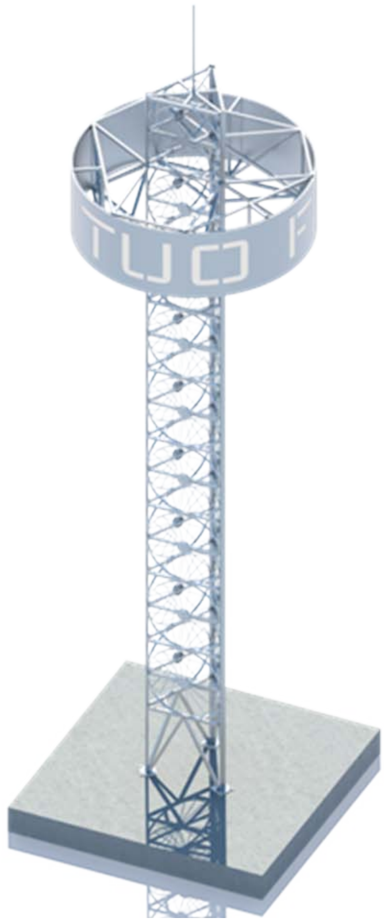

Fig. 8 Advertising hoarding planned construction visualization

Currently, an intensive testing of scale models, which should show if the numerical simulations correspond with the real behaviour of the tested samples, is going on [9], [10].

The possible use of the circular system in practice is suitable especially for lookout towers, potentially also for high-rise buildings requiring an architectonically untraditional design of the construction system. At the moment, there is an advertising hoarding planned construction which should use the new circular bracing system including of seismic (see Fig. 8) [11], [12].

Acknowledgment

The project was carried out with the financial support of specific university research for the years 2011, 2012, 2013, 2014 (SP2014/180) awarded to VŠB-TU Ostrava by the Ministry of Education of the Czech Republic, and also with a foundation contribution of the NIF program “Věda a výzkum pro život 2011” (Science and research for life 2011).

REFERENCES

[1] A. Terranova, "*Skyscrapers"*, Italy, White Star S. r. l., 2003.
[2] S. L. Kramer, *"Geotechnical Earthquake Engineering"*, New York, NY, U.S.A., Prentice Hall, 1996.
[3] EN 1998-1, Eurocode 8: *Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings*, CEN Brussels, December 2004.
[4] R. Fojtík, M. Rosmanit, "A New Pre-Stressed Bracing System for Buildings", *CC2009: The 12th International Conference on Civil, Structural and Enviromental Engineering Computing*, Funchal, Madeira, Portugal, Proceedings and CD, 2009.
[5] R. Furferi, L. Governi, M. Palai, Y. "Volpe, 3D Model Retrieval from Mechanical Drawings Analysis", *International Journal of Mechanics*, lssue 1, 2011, pp. 91-99, ISSN:1998-4448.
[6] L. Vîlceanu, E. Ghita, V. Puțan, "Research on the Working Life at Steel Wire Ropes in Contact", *International Journal of Mechanics*, lssue 1, Volume 6, 2012, pp. 140-147, ISSN:1998-4448.
[7] EN 1990, Eurocode: *Basis of Structural Design*, CEN Brussels, 2002.
[8] P. Dostálek, J. Dolinay, V. Vasek, "Modular Measurement System for Strain Gauge Sensor Evaluation", *International Journal of Mechanics*, lssue 1, 2011, pp. 242-249, ISSN:1998-4448.
[9] V. Tomica, J. Odrobiňák, "Stochastic character of stress hot spots on a highway bridge", *Proceedings of XVIII. Russian-Slovak-Polish international seminary "Theoretical foundation of civil engineering"*, Moscow - Archangelsk, Russia, 2009. Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa 2009.
[10] V. Čecháková, M. Rosmanit, R. Fojtík, "FEM modeling and experimental tests of timber bridge structure", *Procedia Engineering*, 2012, pp.79-84, ISSN:1877-7058.
[11] R. Fojtík, T. Novotný, "The new conception circular system of steel structure bracing". *Proceedings of the 1st WSEAS International Conference on High-Performance Concrete Structures and Materials,* Hungary, Budapest, December 10-12, 2013, pp. 145-149, ISBN 978-960-474-352-0, ISSN 2227-4359.
[12] F. C. Ponzo, A. D. Cesare, D. "Nigro, Visco-Re-Centring Energy Dissipating System for Seismic Protection of Framed Buildings", *International Journal of Mechanics*, lssue 1, Volume 6, 2012, pp. 370-378, ISSN:1998-4448.