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Application of Wire Gauze as a Green and Cost Saving Approach for Seismic Bearing Design

WONG HON FEI*#, KAMARUDIN AB MALEK* AND ISMALIZA BINTI ISMAIL*

The base isolation method using seismic natural rubber bearings has been successfully used to protect structures from earthquakes. This technology not only protects the structures but also its contents and is therefore significant for critical buildings such as hospitals and emergency centres. However, the current design of the seismic rubber bearings require a huge quantity of steel plates which could account for up to 60% of the production cost. In this paper a study on the use of wire gauze which is economically viable in comparison to steel plates is described. The use of steel wire gauze could also obviate the application of adhesives that are required to bond steel plates to the rubber and this could also reduce the cost. Important parameters such as shear and vertical stiffness as well as damping of scaled-down wire-gauze-reinforced-bearings were investigated. The results are compared with the normal steel-plate-laminated bearings and with that obtained from finite element analysis.

Keywords: natural rubber bearings; wire gauze reinforced; steel plates; vertical stiffness; shear damping

Seismic rubber bearings have been successfully used to protect structures from earthquake damage for more than two decades. To date, about 7000[1] buildings and bridges in the world's seismically-prone countries have been installed with rubber bearings. The world's largest application of the seismic rubber bearings is currently undertaken in Iran[1] where 150 blocks of 8 to 12 storey-high buildings are being constructed. The effectiveness of this method was clearly demonstrated during the 1994 Northridge[2] and 1995 Kobe[3] devastating earthquakes where structures on rubber bearings performed very well compared to the conventionally-built buildings and bridges which were either destroyed or suffered serious damage.

The function of rubber bearings (the method is also known as base isolation) is to lengthen the fundamental horizontal period of the structures[4]. Buildings of low and mid height often have fundamental periods which fall within the predominant period of the earthquake, causing the most damaging energy. Therefore, in the event of a major earthquake, resonance would occur and the building's responses would be amplified which could lead to catastrophic damage[5].

Currently, steel plates are used as reinforcements for rubber bearings. The plates used in the current design contribute as much as 60% of the total fabrication cost. Any reduction in the cost of rubber bearings will be

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welcomed by the users especially for the huge project currently undertaken in Iran which will require a significant number of bearings. The use of cheaper wire gauze reinforcements could reduce the cost of each bearing. This paper evaluates the performance of wire-gauze-reinforced bearings in comparison with the conventional bearings.

EXPERIMENTAL METHOD

Fabrication of Scaled-down Seismic Bearings

The size of a seismic rubber bearing will depend on the weight of the building and the expected magnitude of the earthquake at the location where the building is constructed. A typical diameter of a seismic rubber bearing is about 700 mm with a height of 400 mm. Fabrication and testing of these huge rubber bearings are difficult and very costly. In this work, scaled-down bearings were designed so that they could be easily fabricated and tested. This scaled-down bearing was based on the bearings fabricated for the Iranian project[1]. The flow chart in *Figure 1* shows the process involved in the fabrication of a bearing.

Figure 2 shows the scaled-down bearing which consists of 32 layers of metal reinforcements and 33 layers of rubber.

Having established the dimensions of the bearing, a mould was designed as shown in *Figure 3*.

Two types of scaled-down bearings were fabricated: one with steel plate reinforcements and the other with wire gauze. The properties of the wire gauze are shown in the *Table 1*.

Based on *Table 1*, the value of mesh size[6], 10, indicates 10 openings from the centre of any one wire to the centre of a parallel wire 25.4 mm away. A square mesh in a plain weave is applied in this project and it is shown in *Figure 4*.

Since the wire gauze could undergo biaxial extension during compression, various modifications were made in order to minimise this extension so that it would not affect the compression stiffness severely. Each layer of the reinforcement consisted of two pieces of wire gauze oriented at 45° to each other

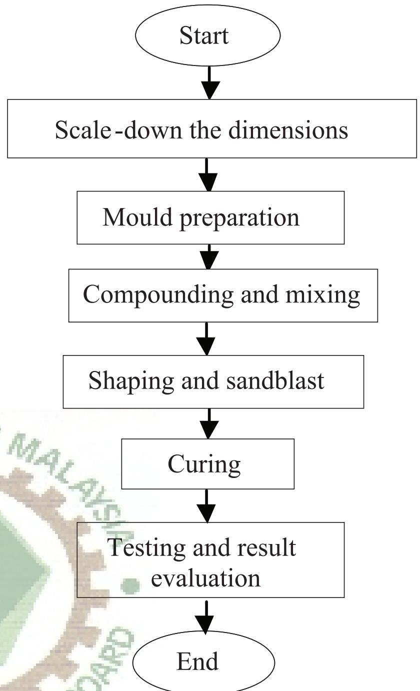

Figure 1. Methodology flow chart of downscaled bearing.

TABLE 1. TYPE OF WIRE GAUZE

Properties	Value
Mesh size	10
Rod diameter	0.5 mm
Material	Galvanised iron
Pattern	Square plain

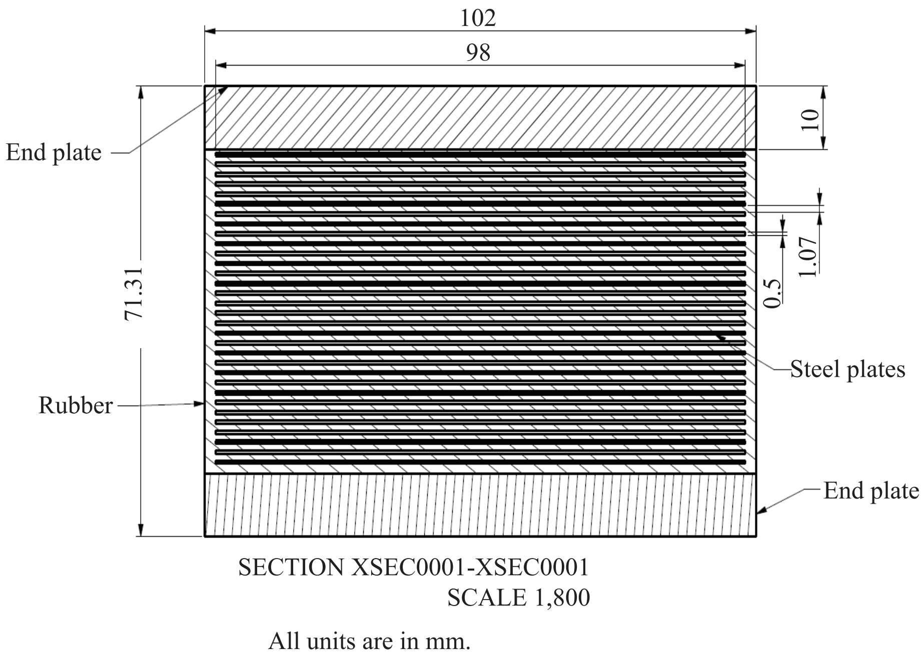

Figure 2. Illustration of scaled-down steel reinforced bearing.

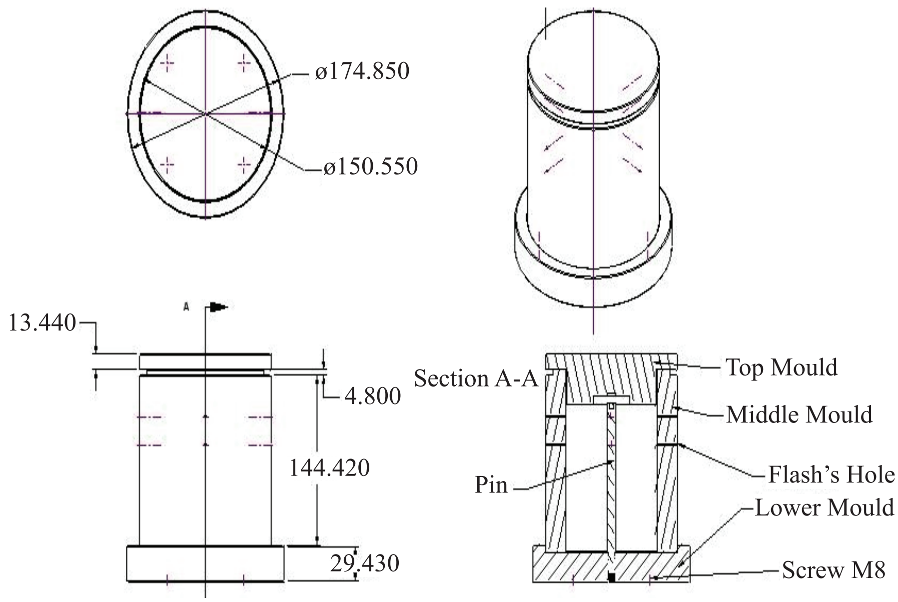

Figure 3. Mould design.

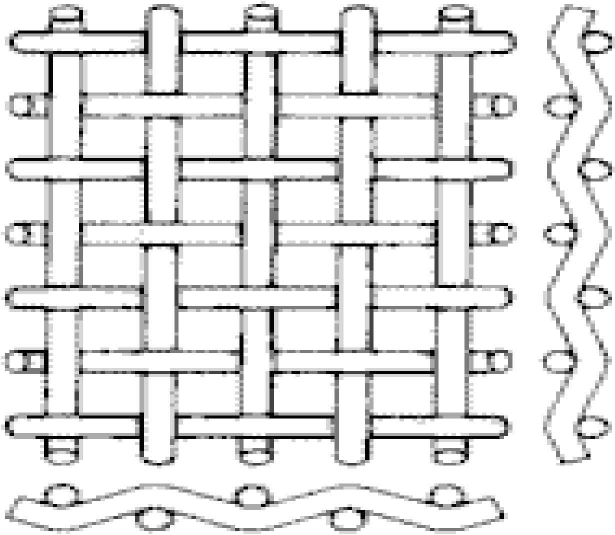

Figure 4. Plain weave[6].

and they were stapled together as shown in *Figure 5*.

Altogether, seven types of wire-gauze-reinforced-seismic bearings were fabricated as shown in *Table 2*. The bearings were No. 3, 4, 5, 6, 8, 10 and 11. Two rubber formulations were used: one was based on high damping rubber mix and the o ther on standard rubber compound as per Engineering Data Sheet 13[7]. For comparison purposes, two types of conventional steel-plate-reinforced bearings as described in *Table 3* were also fabricated.

The compression tests on the bearings were carried out at the compression rate of 1.6 kN/s until the load of 50 kN was reached (*Figure 6*). Subsequently, a simultaneous compression and shear tests were carried out at a shear rate of 0.5 Hz with a compression load of 57 kN (*Figure 7*). The displacement data were recorded by using external linear vertical displacement transmitter (LVDT).

FINITE ELEMENT ANALYSIS (FEA) METHOD

In this investigation, the commercial finite element analysis (FEA) package-ABAQUS CAE Version 6.8 was used to examine the mechanical properties of the bearings. The wire gauze model had been represented using the swept and extrusion method in Pro-E Version4 environment[8]. *Figures 8* and *9* show a single unit cell of the wire gauze model and its hexahedral and tetrahedral meshing.

After the meshing process was carried out, the file size of the wire gauze was over 70 MB, preventing the simulation from being completed. An attempt to simulate an assembly of a unit cell of rubber and a unit cell of wire gauze (*Figure 10*) was also unsuccessful due to the meshing and contact problem[9].

In view of the difficulty to simulate the wire gauze, the latter was assumed to consist

TABLE 2. VARIETY OF WIRE-GAUZE-REINFORCED SEISMIC BEARINGS

Characteristics	Bearing No.						
	3	4	5	6	8	10	11
Rubber formulation	High damping	EDS 13	EDS 13	EDS 13 (modified)	EDS 13 (modified)	EDS 13 (modified)	EDS 13 (modified)
Stapling pattern	Normal	Normal	Normal	Normal	Normal	Normal	Spider web patterning
Diameter of wire gauze layer	ϕ98 mm	ϕ90 mm	ϕ98 mm	ϕ90 mm	ϕ90 mm	ϕ90 mm	ϕ90 mm
Joint or weaving	Weaving	Weaving	Weaving	Weaving and soldering	Weaving and plastic steel filled epoxy	Weaving	Weaving
Chemlok	No	No	No	No	No	Yes	Yes
Size of wire gauze	Mesh size: 10 Rod diameter: 0.5mm	Mesh size: 10 Rod diameter: 0.5mm	Mesh size: 10 Rod diameter: 0.5mm	Mesh size: 10 Rod diameter: 0.5mm	Mesh size: 10 Rod diameter: 0.5mm	Mesh size: 10 Rod diameter: 0.5mm	Mesh size: 10 Rod diameter: 0.5mm

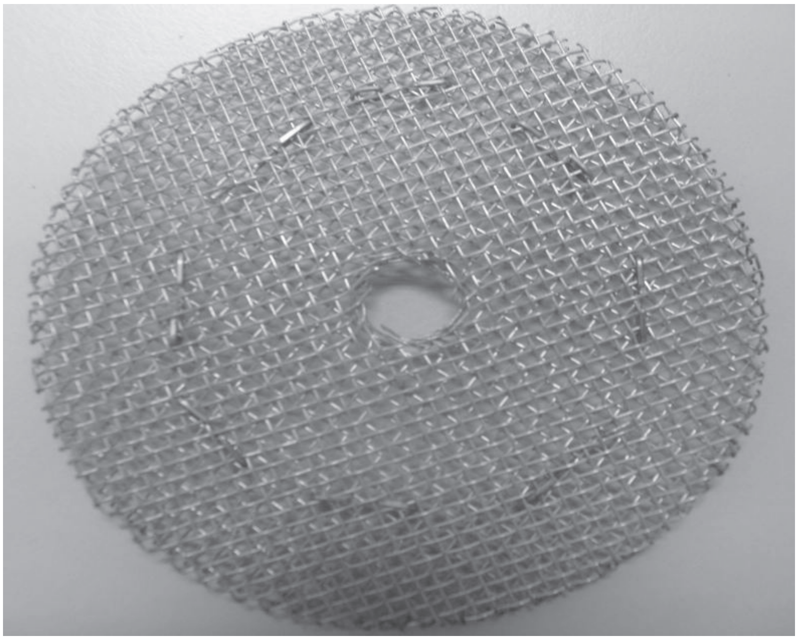

Figure 5. Stapled double wire gauze.

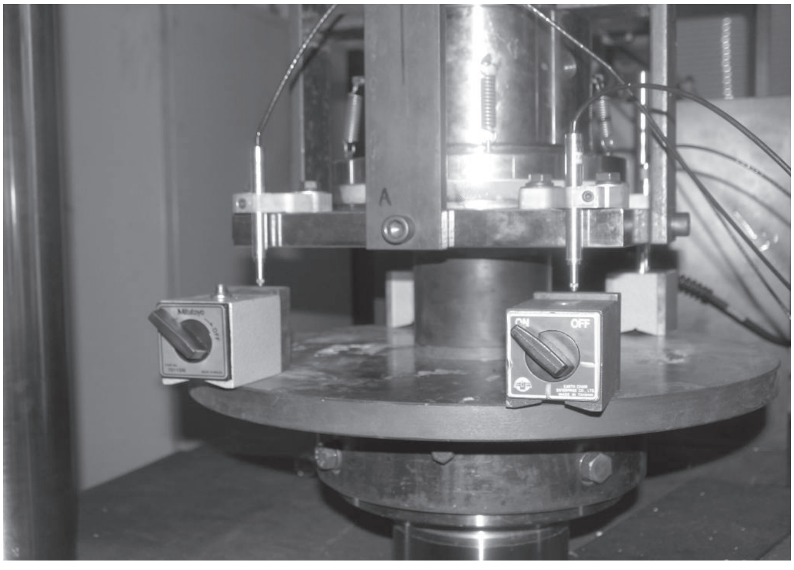

Figure 6. Compression test on the bearing.

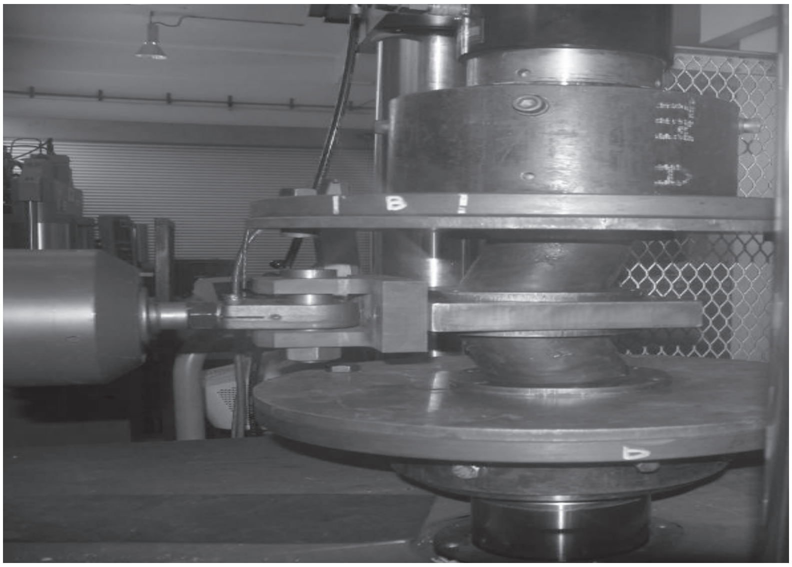

Figure 7. Simultaneous shear and compression test on the bearing.

TABLE 3. STEEL-PLATE-REINFORCED SEISMIC BEARING

Bearing No.	Rubber Formulation	Reinforcement	Size of reinforcement	Remark
1	High damping	Steel	ϕ98 mm	Benchmark
7	EDS 13 (Modified)	Steel	ϕ90 mm	Steel reinforced (Chemlok)

of a very thin metal plate which could undergo biaxial extension like the wire gauze. An equivalent steel plate with thickness of 0.05 mm was assumed for the wire gauze in order to simplify the simulation task.

UNIXIAL TENSION TEST

The shear modulus, *G* can also be determined by carrying out a unaixial tension test on the rubber strip sample to obtain the stress-strain data by using an Instron 5500R as shown in *Figure 11*.

After the stress-strain data had been obtained, the shear modulus, *G* can be determined by importing all the stress-strain data into ABAQUS to carry out the material evaluation process to get the shear modulus. *Figure 12* shows the interface of ABAQUS to find the shear modulus by evaluating the stress-strain data by using Yeoh, Neo-Hooke, Polynomial model and others.

Yeoh model is chosen as the hyperelastic material to model this rubber as it shows a stable result. Its coefficient is shown in *Table 4*.

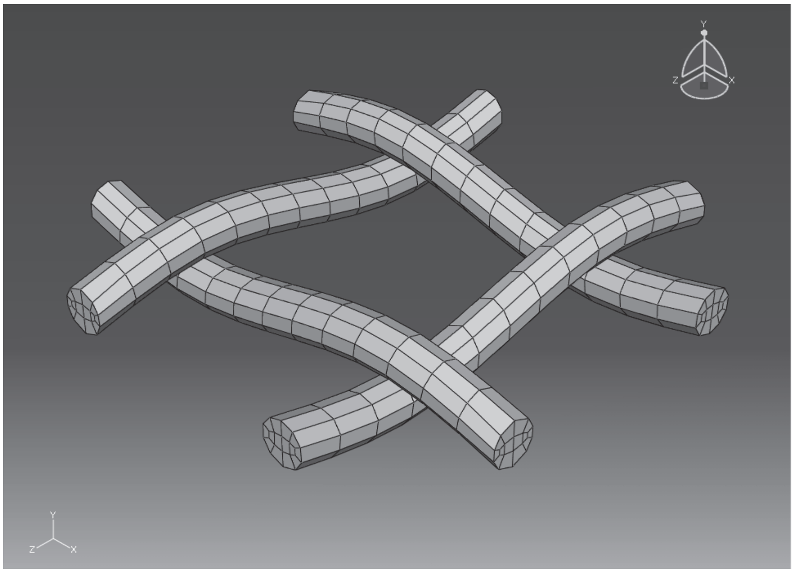

Figure 8. A hexahedral meshing.

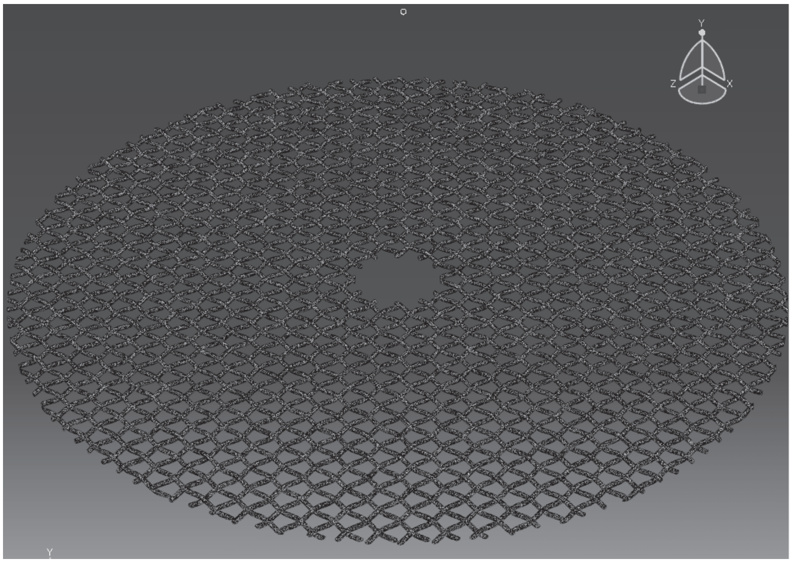

Figure 9. A tetrahedral meshing.

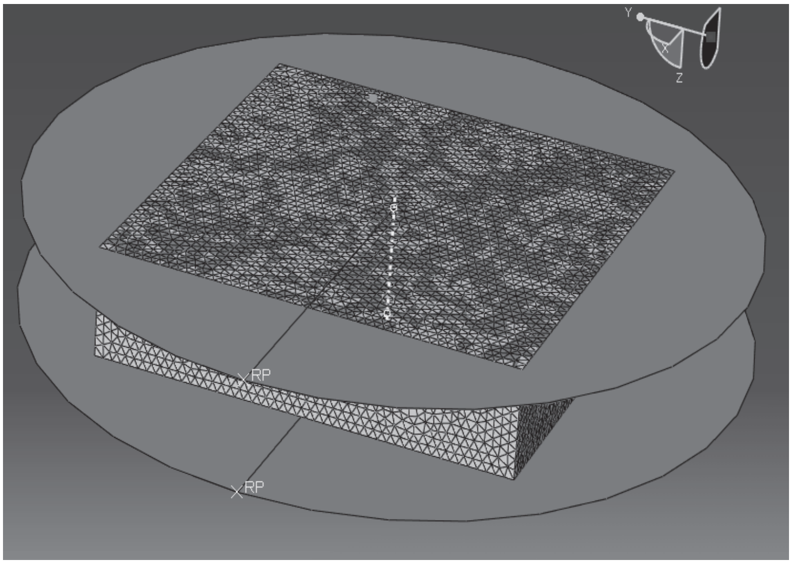

Figure 10. Assembly of a unit cell.

TABLE 4. COEFFICIENT OF YEOH MODEL

Yeoh Model Coefficient	Value
C_{10}	0.365706307
C_{20}	–5.331470719e-4
C_{30}	7.439189726e-4
D_1	0.001
D_2	0
D_3	0

The strain energy function of Yeoh model[10] is defined in *Equation 1*.

$$W = C_{10}(I_1 - 3) + C_{20}(I_1 - 3)^2 + C_{30}(I_1 - 3)^3 \quad \ldots 1$$

where C_{10}, C_{20}, C_{30}, D_1, D_2 and D_3 are constants, I_1, I_2, I_3 are first, second and third invariants respectively.

This model is capable of modeling some of the non-linear features of rubber. Normally C_{10} and C_{30} are positive and C_{20} is negative. Shear modulus, G can be evaluated by using the relation:

$$G = 2 \times C_{10} \quad \ldots 2$$

where the evaluated shear modulus, G is in Mpa.

The shear modulus, G is found to be equal to 1.009 Mpa for the EDS 13 and 2.81 Mpa for the modified EDS 13 material. These values will be used for further calculation.

ANALYTICAL ANALYSIS

Compressive Stiffness

The seismic bearing can also be analysed by an analytical equation. The compression stiffness is defined as:

$$k_{single\_layer\_rubber} = \frac{3GA(1+2s^2)}{t} \qquad \ldots 3$$

where G is shear modulus of the rubber, A is the cross sectional bonded area, t is thickness of the rubber and s is the shape factor of a single layer of rubber.

The compression stiffness of each layer of steel reinforcement is calculated similarly.

$$k_{single\_layer\_steel} = \frac{AE}{l} \qquad \ldots 4$$

where E is Young's modulus of steel.

A parallel spring-connected system is implemented here. A suitable mathematical model of spring-mass system is shown in *Figure 13*.

The total stiffness of this parallel spring system is given by *Equation 5*.

$$\frac{1}{k_{total}} = \sum_{1}^{32}\left(\frac{1}{k_{single\_layer\_steel}}\right)_i + \sum_{1}^{33}\left(\frac{1}{k_{single\_layer\_rubber}}\right)_j \qquad \ldots 5$$

$$k_{total} = 259.91\, kN/mm$$

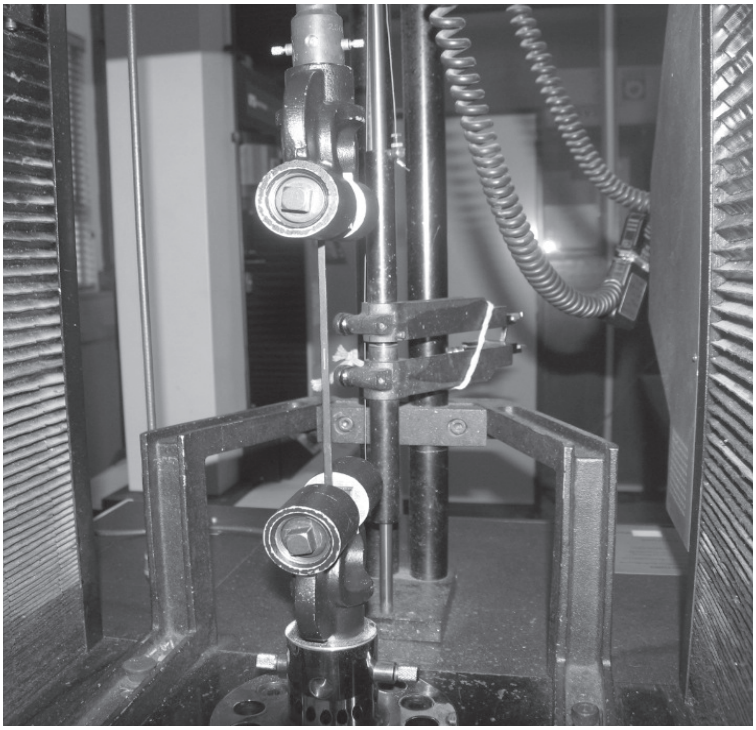

Figure 11. Preliminary setup of Instron 5500R.

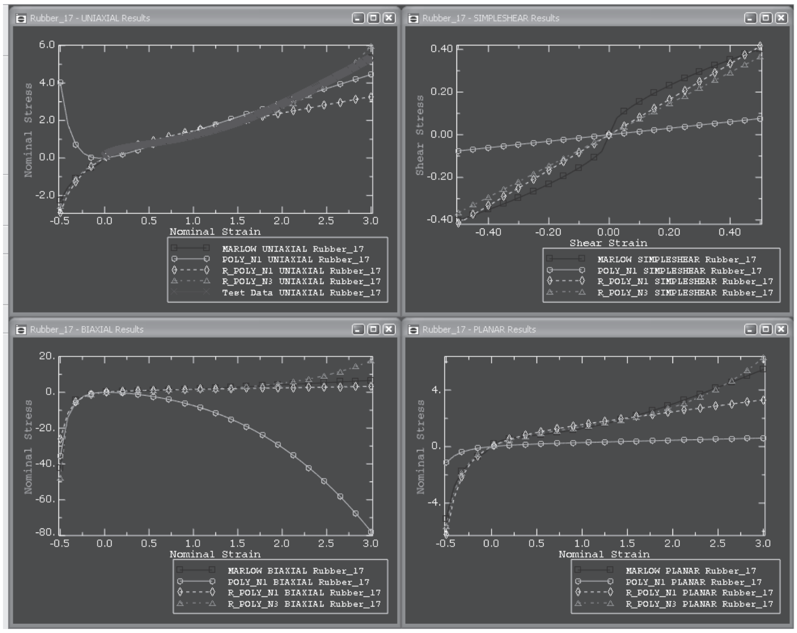

Figure 12. Material evaluation process using ABAQUS.

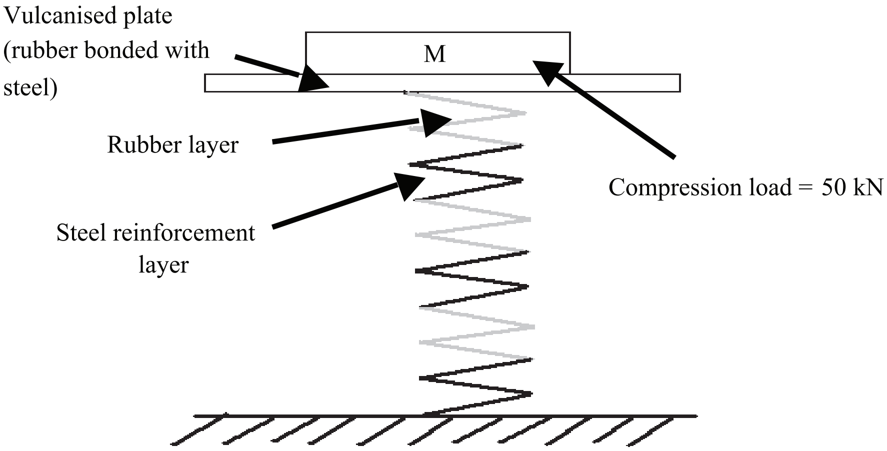

Figure 13. Spring-mass system.

Shear Stiffness

The shear stiffness is defined as:

$$k_{single\_layer\_rubber} = \frac{GA}{t} \quad \ldots 6$$

Similarly, the shear stiffness of the steel reinforced bearing is denoted as:

$$k_{single\_layer\_steel} = \frac{G_{steel}A}{t} \quad \ldots 7$$

Again, to calculate the shear stiffness of this bearing which is comprised of 32 layers of steel reinforcements and 33 layers of rubber, a parallel spring connected system is implemented and *Equation 3* is used. The shear stiffness of the whole bearing is 215.538 N/mm.

Shear Damping

Damping is an important parameter. With a high damping rubber compound, smaller bearings can be designed instead of bigger and more expensive bearings. Depending on the nature of the rubber compound, energy can be dissipated during deformation[11]. This effect is due to friction between the internal planes which slip or slide during the deformations; a typical hysteresis loop obtained during a dynamic test is shown in *Figure 12*.

The area of the loop denotes the energy dissipated by the rubber in a cycle of motion and is given by:

$$\Delta W = \oint F dx = \int_0^{2\pi/\omega} (kX\sin\omega t + cX\omega\cos\omega t)(\omega X\cos\omega t)dt \quad \ldots 8$$

where F is applied load, dx is small displacement, K is stiffness of the object, ω is applied frequency, t is time, c is damping and X is amplitude.

After manipulation of *Equation 8*, it can be proved that the damping ratio, ζ is given by[11]:

$$\zeta = \frac{\Delta W}{2\pi k_s X^2} \quad \ldots 9$$

Equation 9 will be used to calculate the shear damping ratio as shown in *Table 5*, *6* and *7*.

RESULTS AND DISCUSSION

Machine Compliance for Compression Test

Correction for machine compliance is an important step in analysing the data obtained in a compression test[12]. In the determination of this compliance, a mild steel disc with a diameter of 102 mm and thickness of 15.90 mm was compressed using the MTS servo-hydraulic machine 810. *Figure 15* below shows the test setup with installed LVDT to measure the vertical displacements.

The machine compliance, C_m can be evaluated using *Equation 10*.

$$C_a = C_s + C_m \quad \ldots 10$$

where C_a is the ratio between recorded displacement to compressive load, and C_s is the compliance of the disc and is equal to 9.266×10^{-6} mm/kN. Thus, the value of $1/C_m$ is 317.59 kN/mm.

Figures 16 and *17* show the compressive and compression/shear test results of bearing 1 which was reinforced with a steel plate respectively. The recorded compressive stiffness of bearing 1 is 137.568 kN/mm. Correcting the machine compliance effect by modifying *Equation 8* gives the corrected stiffness of the bearing as indicated in *Equation 11*.

$$1/K_C = C_a - C_m \quad \ldots 11$$

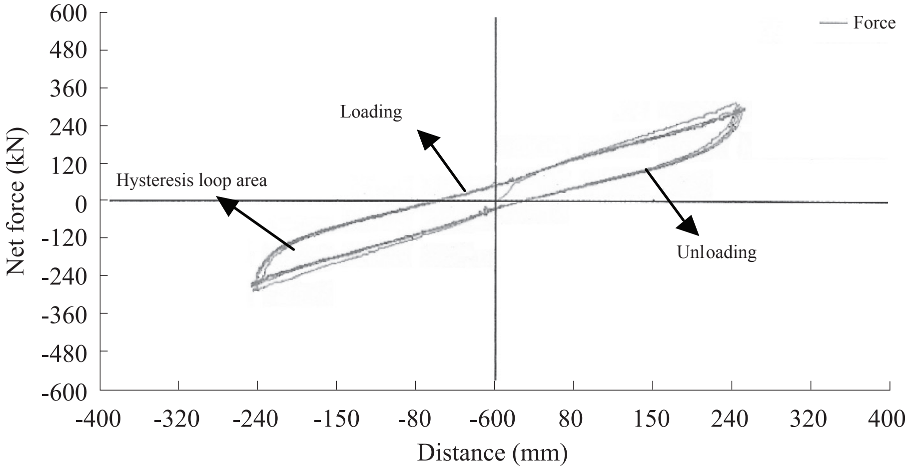

Figure 14. Hysteresis loop.

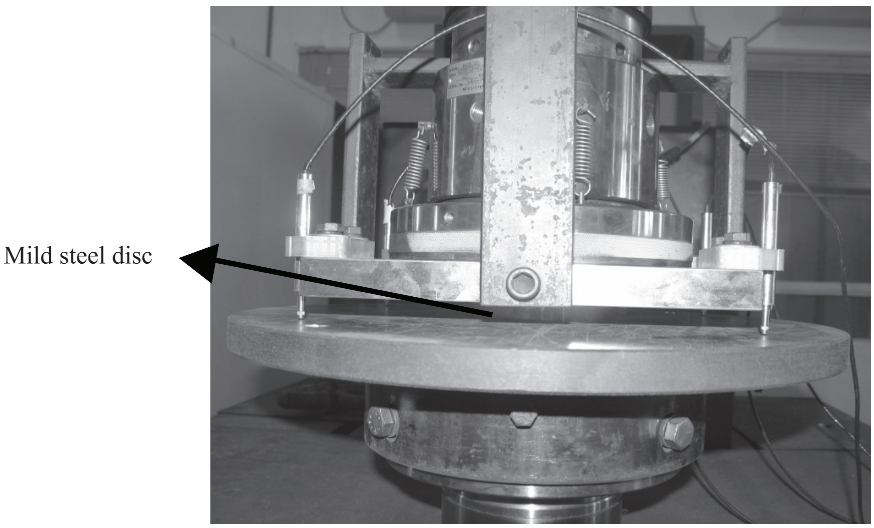

Figure 15. Experimental set-up to determine machine compliance.

The machine compliance effect will only be considered in evaluating the compressive stiffness of the bearing. However, this effect is not taken into account in evaluating shear stiffness because it is not comparable with the shear deformation. The detailed results of bearing 1 are shown in *Figures 16*, *17* and *Table 5*.

Figure 16 shows the results of the compression tests carried out on different wire-gauze-reinforced bearings and the results were compared with a steel plate reinforced bearing (bearing 1). The corresponding results had been adopted from the third cycle[13] for compression/shear tests of bearing 1 as shown in *Figure 17*. The compressive stiffness, damping and shear stiffness results for the bearing using a high damping compound are shown in *Table 5*. For the bearings based on normal damping compound the corresponding results are shown in *Table 6*. It is clear from these results that a high damping rubber bearing can be obtained from wire-gauze-reinforced bearing even when using a normal rubber compound. However, the resulting biaxial extension of the wire gauze significantly reduced the vertical stiffness. Modifying the wire gauze by various techniques such as stapling and application of adhesive did not increase the vertical stiffness of the conventional bearing. This significantly reduced vertical stiffness will not be able to support the weight of the structures and hence the bearings would not function effectively.

Based on *Tables 6* and *7*, shear stiffness is not much altered by the different types of reinforcement used[14]. However, the compressive stiffness depends on the types of reinforcement used. Bearings 6, 8 and 10 show a higher shear stiffness than steel reinforced bearing 7 because of the different rubber compound adopted as shown in *Table 2*.

Result of FEA

Figure 20 shows a simulated model of the seismic rubber bearing reinforced with steel plates.

The FEA results of the wire-gauze-reinforced bearing equivalent with a metal plate of 0.05 mm is compared with the 0.5 mm steel-plate-reinforced-bearing and the results are shown in *Figures 21* and *22*. As expected, the equivalent wire-gauzed-reinforced bearing showed slightly lower compression stiffness due to a probable biaxial extension.

TABLE 5. RESULT OF DAMPING, SHEAR STIFFNESS AND SHEAR MODULUS

Strain (%)	Cycle	Loop Area (kN.mm)	Damping ratio, ζ (%)	K_s (N/mm)	Shear modulus, G (Mpa)
118.00	3rd	291.19	12.78	215.54	1.009

TABLE 6. RESULT OF STEEL REINFORCED BEARING

Bearing No. (High damping formulation)	Compressive stiffness (kN/mm)	Damping, (%)	Shear Stiffness (N/mm)
1A (Metal plate, dia 98 mm)	242.69	12.79	215.54
3A (Wire Gauze,dia 98 mm)	38.04	25.92	172.89

TABLE 7. RESULT OF WIRE GAUZE REINFORCED BEARING

Bearing No. (EDS 13 Formulation)	Compressive stiffness (kN/mm)	Damping, (%)	Shear Stiffness (N/mm)
7 (Metal plate, dia 90 mm)	225.16	8.58	299.30
4 (Wire Gauze, dia 90 mm)	69.38	13.87	262.55
5 (Wire Gauze, dia 98 mm)	95.27	–	–
6 (Wire Gauze, dia 90 mm)	85.84	14.68	422.19
8 (Wire Gauze, dia 90 mm)	82.10	19.16	512.59
10 (Wire Gauze, dia 90 mm)	115.46	12.92	505.37
11 (Wire Gauze, dia 90 mm)	121.55	–	–

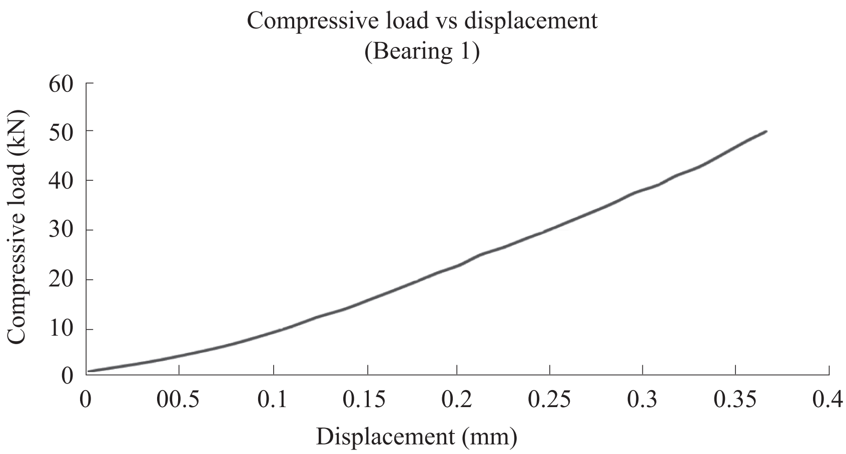

Figure 16. Compression load versus displacement.

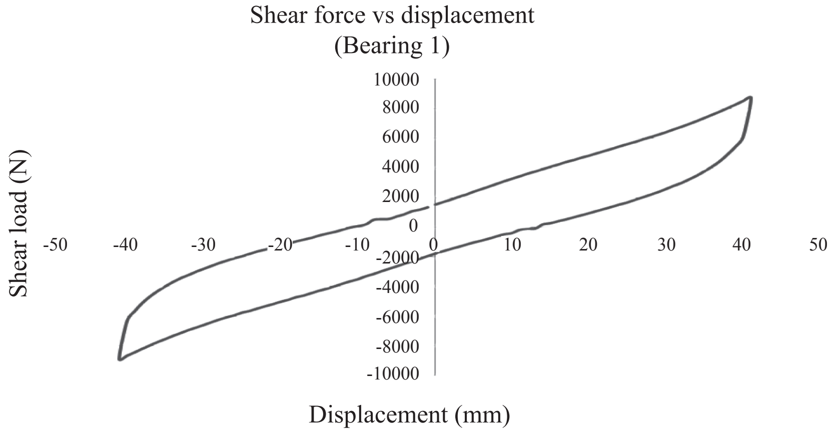

Figure 17. Shear force versus shear displacement.

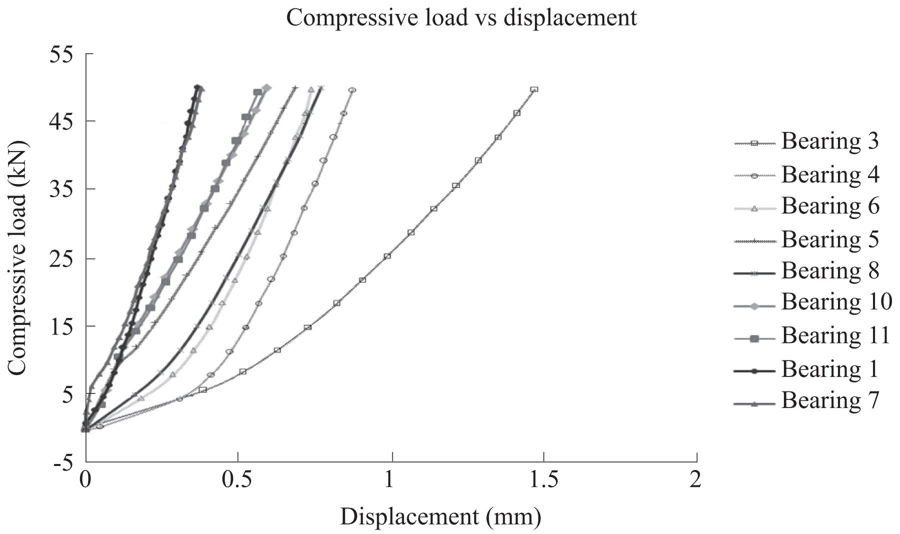

Figure 18. Result of wire gauze reinforced bearing (compressive stiffness).

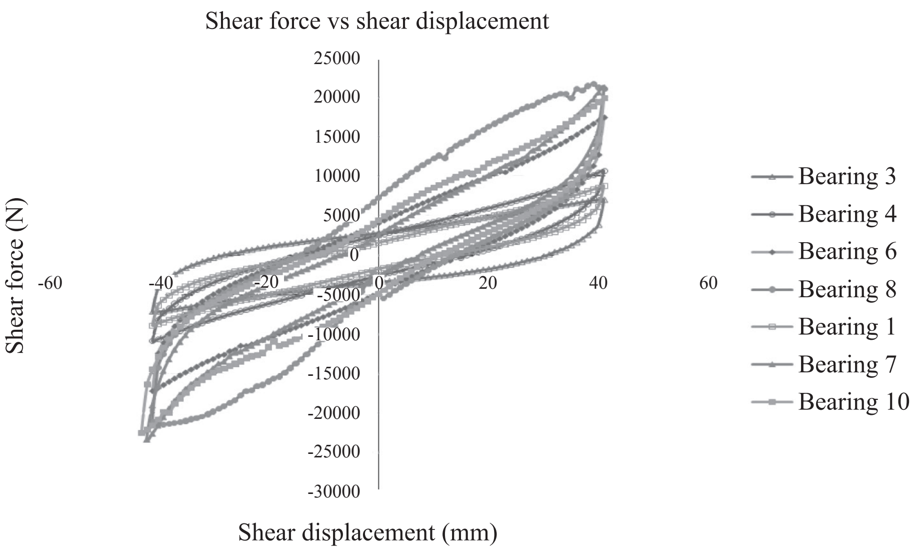

Figure 19. Result of wire gauze reinforced bearing.

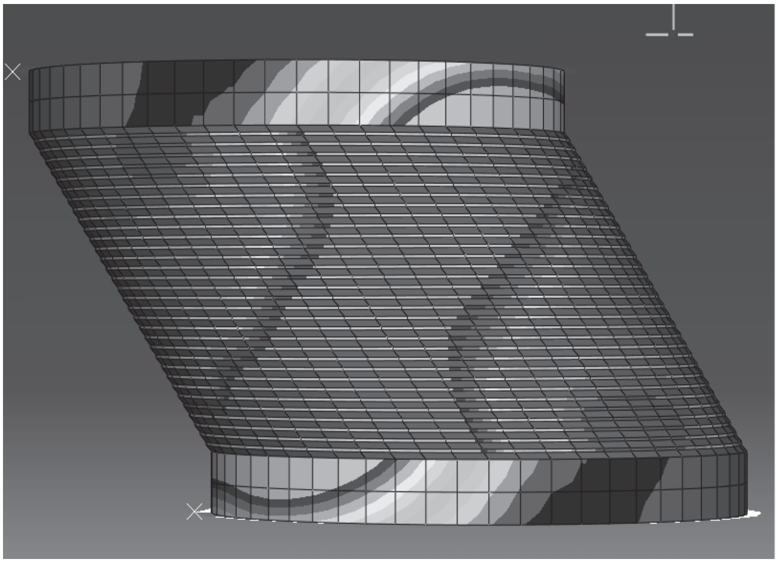

Figure 20. Simulation of scaled-down steel plate reinforced bearing.

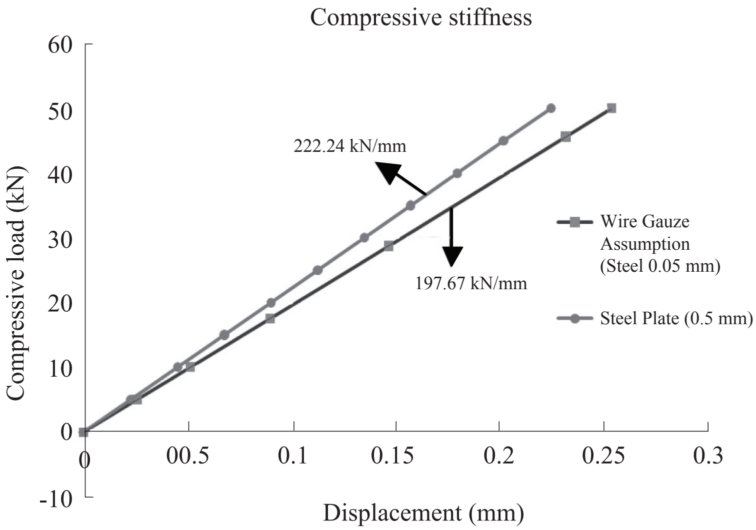

Figure 21. Comparison of FEA results (compressive stiffness).

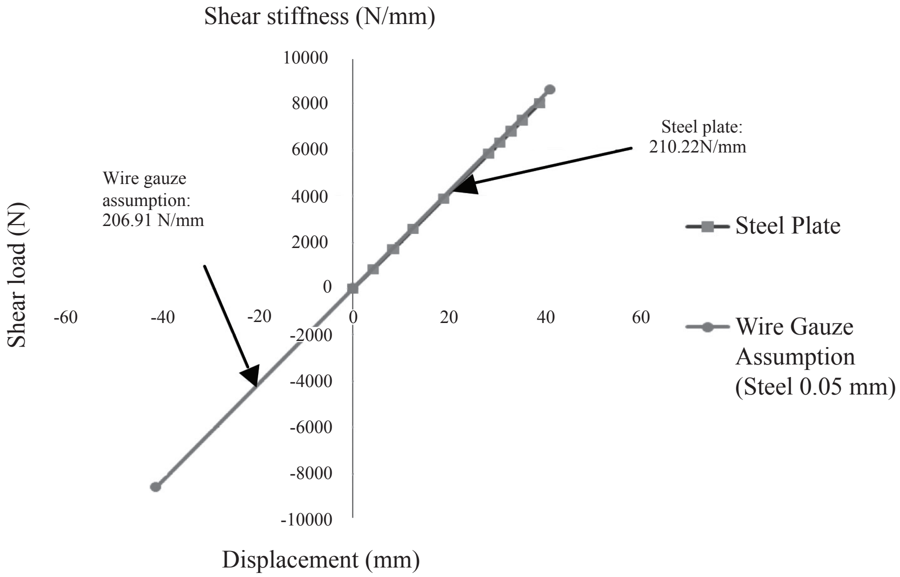

Figure 22. Comparison of FEA results (shear stiffness).

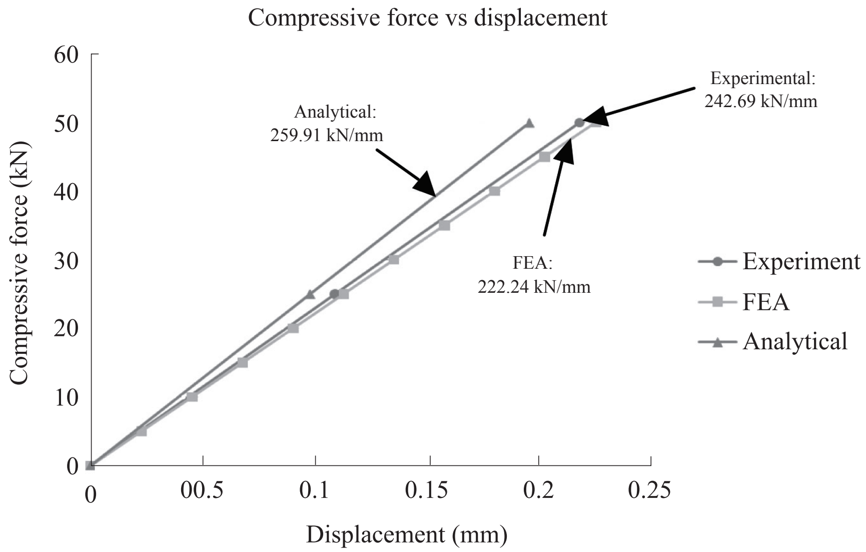

Figure 23. Comparison of bearing 1 results (compressive stiffness).

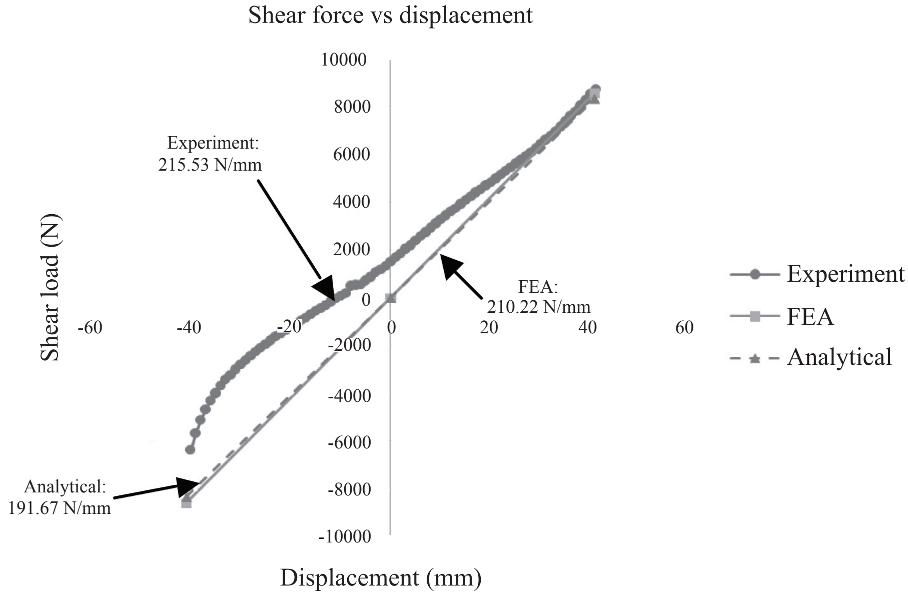

Figure 24. Comparison of bearing 1 results (shear stiffness).

TABLE 8. COMPARISON OF COST

Bearing Items	Bearing 1A (steel reinforced)	Bearing 3A (wire gauze reinforced)	% Difference
Reinforced material	RM8.32	RM5.12	–38.46%
Rubber	RM2.55	RM4.40	+72.55%
Chemlok	RM2.50	–	–
Total Cost	RM13.37	RM9.52	–28.80%

Figures 23 and *24* show results of FEA, both experimental and analytical for steel-plate-reinforced-bearing 1. With the exception of the analytical result, the compressive stiffness obtained from the experiment and FEA is in agreement. This may be because of the theoretical assumption that only a small bulging effect which adopts the parabolic forms[15]. On the other hand, the shear stiffness obtained from the experiment, FEA and analytically show a minor difference.

Cost Comparison

By calculating the cost of the individual components of a bearing, cost comparison of steel-plate-reinforced and wire-gauze-reinforced bearings can be made as shown in *Table 8*. It can be seen from the *Table 8* that fabricating a wire-gauze-reinforced-bearing could produce a savings of about 28.8%.

CONCLUSIONS

Replacing steel plates with wire gauze could reduce the amount of steel used in a bearing by about 30%. Moreover this reduction and the elimination of the use of adhesives could reduce the fabrication cost of a bearing by about 28%. However, due to a biaxial extension of the wire gauze during compression the compression stiffness was significantly reduced hampering the ability for the bearing to support the load of the structure. On the other hand the wire gauze reinforced bearing produced a significant increase in damping even when using an ordinary rubber compound. This is an advantage because a high damping rubber tends to have drawbacks in terms of strength and temperature sensitivity. It is therefore important that the method used to increase the compressive stiffness is evaluated so that appropriate properties of the wire gauze reinforced bearing can be applied.

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REFERENCES

1. AB-MALEK, K. (2008) Seismic Rubber Bearings for Effective Protection of Structures and their Contents. *Buletin IEM* (3).
2. KELLY, J.M., NAEIM AND FAZRZAD. (1999) From Theory to Practice, in *Design of Seismic Isolated Structures*. Canada: USA: John Wiley. 18–20.
3. KELLY, J. M., NAEIM AND FAZRZAD. (1999). From Theory to Practice, in *Design of Seismic Isolated Structures*. Canada: USA: John Wiley. 22–23.
4. KEY AND DAVID. (1988) *Earthquake Design Practice for Buildings*. London: Thomas Telford. 76–78.
5. MUNIANDY, K. (1991, September). Design of Elastomeric Bearings for Vibration and Seismic Isolation. *Natural Rubber in Engineering*.
6. LENNTECH (1998) *http://www.lenntech.com/wovenwire.htm*. Retrieved 14.8.2007.
7. Engineering Data Sheet 13. Brickendonbury, Hertford SG138NL, England: The Malaysian Rubber Producers' Research Association.
8. PTC. (2008) Creating sweeps and blends. In *Introduction to Pro/ENGINEER Wildfire 4.0*. PTC, pp. 11.1–11.22.
9. ABAQUS VERSION 6.7. (2007) Chapter 12: Contact, in *Getting Started with Abaqus*. North America: Simulia. 12.1–12.14.
10. BRITISH STANDARD (2004). Part 5: Guide to the Application of Rubber Testring to Finite Element Analysis, in *Physical Testing of Rubber*.
11. RAO, S.S. (1990) *Mechanical Vibrations, Second edn*., Purdue University.
12. KALIDINDI, S.R., ABUSAFIEH, A., AND EL-DANAF, E. (1966). Accurate Characterisatrion of Machine Compliance for Simple Compression Testing. *Experimental Mechanics*, **37**.

13. ODGEN, R.W. AND ROBURGH, D.G. (1999) A Pseudo-Elastic Model for the Mullins Effect in the Filled Rubber. Proceedings — Royal Society of London A. **455**, 2861–2877.

14. LINDLEY, P.B. (1984) Engineering Design with Natural Rubber, in *K.N. Fuller (Ed.)*. The Malaysian Rubber Producers' Research Association.

15. FREAKLEY, P.K. (1978) Analysis of the Deformation of Rubber Units Under Equilibrium Loading Conditions, in *Theory and Practice of Engineering with Rubber*. London: Applied Science Publishers. 113–165.