PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

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ABSTRACT

Fiber-reinforced elastomeric bearings were originally proposed as an alternative to conventional steel-reinforced elastomeric bearings for seismic isolation applications. The flexible fiber reinforcement is a light-weight and potentially cost-saving alternative to steel reinforcement, which is assumed rigid in the design process. The variety of fiber materials available also serves as an additional parameter for designers to tailor the vertical stiffness of the bearing. In this report, a further cost reduction is visualized by manufacturing the bearing in a large sheet that can be cut to the required size such that the ideal shape for the bearing will be rectangular. An analytical solution for the vertical compression modulus of a rectangular elastomeric pad including the effects of the elastomer bulk compressibility and extensibility of the fiber reinforcement is given here in the form of a rapidly convergent single series. This solution is computationally efficient and allows for a rapid calculation of the stiffness for both design and analysis purposes.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of the Natural Sciences and Engineering Research Council of Canada and a Vanier Canada Graduate Scholarship.

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1 Introduction

An analysis is given for the mechanical characteristics of rectangular multilayer elastomeric isolation bearings when the reinforcing elements, which are normally steel plates, are replaced by a fiber reinforcement. The fiber reinforcement, in contrast to the steel reinforcement (which is assumed to be rigid both in extension and flexure), is assumed to be flexible in extension, but completely without flexural rigidity. The influence of fiber extensibility on the vertical stiffness of the fiber-reinforced isolator is studied, and it is shown that it should be possible to produce a fiber-reinforced isolator that matches the behavior of a steel-reinforced isolator. The fiber-reinforced isolator will be significantly lighter and could be significantly less expensive to manufacture since the bearings can be mass produced by a much less labor intensive manufacturing process in contrast to current steel-reinforced bearings, which are custom made. The analysis for strip [Kelly and Takhirov 2002], circular [Kelly and Calabrese 2013], annular [Pinarbasi and Okay 2011] and rectangular bearings using a double Fourier series solution [Angeli et al. 2013] has been given in a series of earlier reports.

Seismic isolation technology in the U.S. is applied almost exclusively to large, expensive buildings housing sensitive internal equipment, e.g.,, computer centers, chip fabrication factories, emergency operation centers, and hospitals. The isolators used in these applications are large, expensive, and heavy. An individual isolator can weight one ton and often more. To extend this valuable earthquake-resistant strategy to housing and commercial buildings, it is necessary to reduce the cost and weight of the isolators. The primary weight in an isolator is due to the reinforcing steel plates that are used to provide the vertical stiffness of the rubber–steel composite element. A typical rubber isolator has two large endplates (around 1 in. thick) and 20 thin reinforcing plates (1/8 in. thick). The high cost of producing the isolator results from the labor involved in preparing the steel plates and the assembly of the rubber sheets and steel plates for vulcanization bonding in a mold. The steel plates are cut, sandblasted, acid cleaned, and then coated with a bonding compound. Next, the compounded rubber sheets with the interleaved steel plates are put into a mold and heated under pressure for several hours to complete the manufacturing process.

The purpose of the research program, of which this study is a part, is to suggest that both the weight and the cost of isolators can be reduced by eliminating the steel reinforcing plates and replacing them with fiber reinforcement. The weight reduction is possible as fiber materials are available with an elastic stiffness that is of the same order as steel. Thus the reinforcement needed to provide the vertical stiffness may be obtained by using a similar volume of very much lighter material. The cost savings may be possible if the use of fiber allows a simpler, less labor-intensive manufacturing process. It is also possible that the current approach of vulcanization under pressure in a mold with steam heating can be replaced by microwave heating in an autoclave. Another benefit of using fiber reinforcement is that it would then be possible to build isolators in long rectangular strips, whereby individual isolators could be cut to the required size. All isolators are currently manufactured as either circular or square in the mistaken belief that if the isolation system for a building is to be isotropic, it needs to be made of symmetrically shaped isolators. Rectangular isolators in the form of long strips would have distinct advantages over square or circular isolators when applied to buildings where the lateral resistance is provided by walls. When isolation is applied to buildings with structural walls, additional wall beams are needed to carry the wall from isolator to isolator. A strip isolator would have a distinct advantage for retrofitting masonry structures and for isolating residential housing constructed from concrete or masonry blocks. To date, an analytical solution for a rectangular pad with a single Fourier series solution has not been available. This report presents a single series solution for the vertical stiffness of a rectangular pad that includes elastomer compressibility as well as reinforcement extensibility, with the square pad as a special case.

2 Vertical Stiffness

2.1 ELASTOMERIC PAD

Consider a layer of elastomer in an arbitrarily shaped pad of thickness, t, and a rectangular Cartesian coordinate system (x, y, z) in the middle surface of the pad, as illustrated in Figure 2.1. The displacements of the elastomer along the coordinate directions are:

$$\begin{aligned} u(x,y,z) &= u_0(x,y)\left(1-\frac{4z^2}{t^2}\right)+u_1(x,y) \\ v(x,y,z) &= v_0(x,y)\left(1-\frac{4z^2}{t^2}\right)+v_1(x,y) \\ w(x,y,z) &= w(z) \end{aligned} \tag{2.1}$$

where u_0 and v_0 are related to the lateral bulging of the elastomer, and u_1 and v_1 are related to the extension of the fiber reinforcement. These displacements represent the kinematic assumption that the lateral bulging of the elastomeric layers follows a parabolic curve and that the horizontal planes remain plane and horizontal [Kelly 1993].

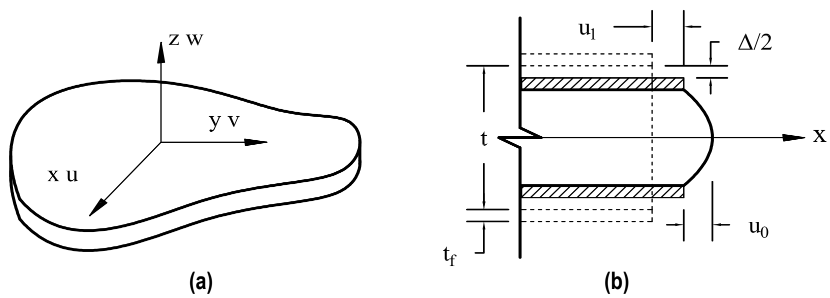

Figure 2.1 **Constrained elastomeric pad (a) coordinate system and (b) lateral bulging.**

It is assumed that the elastomeric compound is linear elastic and is not incompressible, but is affected by bulk compressibility which leads to the equation of compressibility constraint:

$$\varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz} = -\frac{p}{K} \tag{2.2}$$

where K is the bulk modulus and from Equation (2.1):

$$\varepsilon_{xx} = u_{o,x}\left(1 - \frac{4z^2}{t^2}\right) + u_{1,x}$$

$$\varepsilon_{yy} = v_{o,y}\left(1 - \frac{4z^2}{t^2}\right) + v_{1,y} \tag{2.3}$$

$$\varepsilon_{zz} = w_{,z}$$

are the strains in which the commas imply a partial differentiation with respect to the indicated coordinate.

Substitution of Equation (2.3) into Equation (2.2) yields:

$$u_{o,x}\left(1 - \frac{4z^2}{t^2}\right) + u_{1,x} + v_{o,y}\left(1 - \frac{4z^2}{t^2}\right) + v_{1,y} + w_{,z} = -\frac{p}{K} \tag{2.4}$$

which, when integrated through the thickness from $-t/2$ to $t/2$, gives:

$$\frac{2}{3}\left(u_{o,x} + v_{o,y}\right) + u_{1,x} + v_{1,y} + \frac{w(t/2) - w(-t/2)}{t} = -\frac{p}{K} \tag{2.5}$$

where $w(t/2) = -\Delta/2$ and $w(-t/2) = \Delta/2$, and Δ is the vertical deflection; see Figure 2.1.

Equivalently:

$$u_{o,x} + v_{o,y} + \frac{3}{2}\left(u_{1,x} + v_{1,y}\right) = \frac{3}{2}\varepsilon_c - \frac{3}{2}\frac{p}{K} \tag{2.6}$$

where, $\varepsilon_c = \Delta/t$, is the vertical compression strain in the pad. Note that compression is taken as positive.

Assuming that the stress state is dominated by the internal pressure, p, such that $\sigma_{xx} \approx \sigma_{yy} \approx \sigma_{zz} \approx -p$, and that there is no shear stress in the *x-y* plane, $\tau_{xy} = \tau_{yx} = 0$ [Kelly 1993], the equations of equilibrium for the stresses:

$$\sigma_{xx,x} + \tau_{xy,y} + \tau_{xz,z} = 0$$

$$\tau_{xy,x} + \sigma_{yy,y} + \tau_{yz,z} = 0 \tag{2.7}$$

$$\tau_{xz,x} + \tau_{yz,y} + \sigma_{zz,z} = 0$$

reduce to

$$\tau_{xz,z} = -\sigma_{xx,x} = p_{,x}$$
$$\tau_{yz,z} = -\sigma_{yy,y} = p_{,y} \quad (2.8)$$

Assuming that the material is linear elastic, shear stresses τ_{xz} and τ_{yz} are related to shear strains $\gamma_{xz} = \left(u,_z + w,_x\right)$ and $\gamma_{yz} = \left(\mathrm{v},_z + w,_y\right)$ by:

$$\tau_{xz} = G\gamma_{xz}$$
$$\tau_{yz} = G\gamma_{xz} \quad (2.9)$$

with G being the shear modulus of the material. Thus, from Equation (2.3):

$$\tau_{xz} = -Gu_0 \frac{8z}{t^2}$$
$$\tau_{yz} = -Gv_o \frac{8z}{t^2} \quad (2.10)$$

The equilibrium conditions from Equation (2.8) now become:

$$\sigma_{xx,x} = \frac{8Gu_0}{t^2} = -p_{,x}$$
$$\sigma_{yy,y} = \frac{8Gv_o}{t^2} = -p_{,y} \quad (2.11)$$

2.2 STRESS IN THE FIBER REINFORCEMENT

The fiber reinforcement is visualized as two thin sheets of straight fibers in the *x*- and *y*-directions with a total thickness t_f. This is the most commonly used type of fiber reinforcement, and the composite sheet is unable to sustain any internal shear forces. The normal forces in the sheet per unit length are F_{xx} and F_{yy}, which are related to the surface shear stresses at the top and bottom of the elastomeric layers adjacent to the sheet, shown in Figure 2.2 for the *x*-direction.

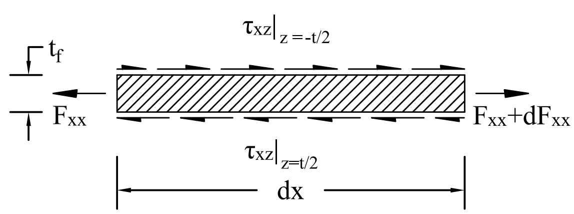

Figure 2.2 Forces acting on the extensible reinforcement.

Equilibrium in the reinforcement requires that:

$$F_{xx,x} - \tau_{xz}\Big|_{z=+\frac{t}{2}} + \tau_{xz}\Big|_{z=-\frac{t}{2}} = 0$$
$$F_{yy,y} - \tau_{yz}\Big|_{z=+\frac{t}{2}} + \tau_{yz}\Big|_{z=-\frac{t}{2}} = 0 \qquad (2.12)$$

From Equation (2.10):

$$\tau_{xz}\Big|_{z=+\frac{t}{2}} = -\frac{8Gu_0}{2t}$$
$$\tau_{xz}\Big|_{z=-\frac{t}{2}} = \frac{8Gu_0}{2t} \qquad (2.13)$$

and

$$\tau_{yz}\Big|_{z=+\frac{t}{2}} = -\frac{8Gv_0}{2t}$$
$$\tau_{yz}\Big|_{z=-\frac{t}{2}} = \frac{8Gv_0}{2t} \qquad (2.14)$$

Equation (2.12) can be expressed as:

$$F_{xx,x} + \frac{8Gu_o}{t} = 0$$
$$F_{yy,y} + \frac{8Gv_o}{t} = 0 \qquad (2.15)$$

The relationship between the internal forces in the sheet and the displacements are:

$$F_{xx} = E_f t_f u_{1,x}$$
$$F_{yy} = E_f t_f v_{1,y} \qquad (2.16)$$

where E_f is the effective elastic modulus of the reinforcement layers. In Angeli et al. [2013], which presented the analytical solution of a rectangular pad with a double Fourier series solution, the thickness of the fiber layer was divided by two assuming half the fibers are oriented in one direction and the other half in the perpendicular direction. Here, the full thickness of the reinforcement layer is used. Note that for this approach the value of E_f should reflect the effective elastic modulus of the fiber reinforcement matrix.

2.3 COMPLETE SYSTEM OF EQUATIONS

Substituting the relations in Equation (2.16) into Equation (2.15) gives:

$$E_f t_f u_{1,xx} + \frac{8Gu_0}{t} = 0$$
$$E_f t_f v_{1,yy} + \frac{8Gv_0}{t} = 0 \qquad (2.17)$$

There are five equations for the five unknowns: u_o, v_o, u_1, v_1, and p.

Consider the specific example of the rectangular bearing with sides a and $2b$ over the range $0 \le x \le a$ and $-b \le y \le b$ as shown in Figure 2.3. The boundary conditions at the edges of the bearing are zero pressure in the elastomeric layer and zero force in the fiber reinforcement.

The terms in u_o and v_o in Equation (2.17) can be eliminated by substituting in Equation (2.11). Expressing in favor of the pressure:

$$\begin{aligned} p_{,x} &= \frac{E_f t_f}{t} u_{1,xx} \\ p_{,y} &= \frac{E_f t_f}{t} v_{1,yy} \end{aligned} \tag{2.18}$$

Using the boundary conditions on p and F_{xx} at $x = 0$ and $x = a$, and those on p and F_{yy} at $y = \pm b$, Equation (2.18) can be integrated to give:

$$\begin{aligned} p &= \frac{E_f t_f}{t} u_{1,x} \\ p &= \frac{E_f t_f}{t} v_{1,y} \end{aligned} \tag{2.19}$$

It can be concluded from Equation (2.19) that the strain, and, consequently, the force per unit length in the fiber reinforcement, is equal in the *x*- and *y* -directions at any given point (i.e., $u_{1,x} = v_{1,y}$).

Substituting Equation (2.11) and Equation (2.19) into the compressibility constraint, Equation (2.6), yields:

$$-\frac{t^2}{12G}\left(p_{,xx} + p_{,yy}\right) + \frac{2t}{E_f t_f} p = \varepsilon_c - \frac{p}{K} \tag{2.20}$$

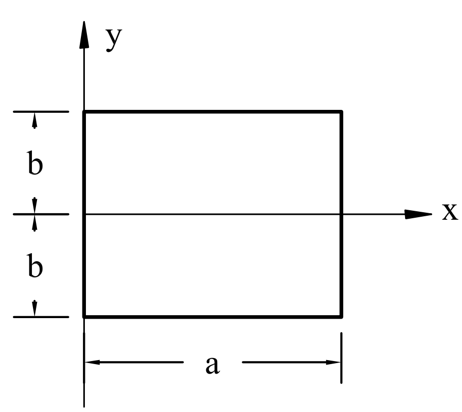

Figure 2.3 Rectangular pad coordinate system.

which can be rearranged as:

$$p_{,xx} + p_{,yy} - \left(\frac{24G}{E_f t_f t} + \frac{12G}{t^2 K} \right) p = -\frac{12G}{t^2} \varepsilon_c \tag{2.21}$$

with the boundary conditions $p = 0$ on $x = 0$ and $x = a$, and $y = \pm b$.

It is convenient to define a set of dimensionless variables:

$$\alpha^2 = \frac{24Ga^2}{E_f t_f t}$$
$$\beta^2 = \frac{12Ga^2}{t^2 K} \tag{2.22}$$

and $\xi = \frac{x}{a}, \eta = \frac{y}{b}$ and $\bar{p} = \frac{p}{K}$. With these definitions, Equation (2.21) becomes:

$$\bar{p}_{,\xi\xi} + \frac{a^2}{b^2} \bar{p}_{,\eta\eta} - \left(\alpha^2 + \beta^2 \right) \bar{p} = -\beta^2 \varepsilon_c \tag{2.23}$$

A solution of the form:

$$\bar{p}(\xi, \eta) = \sum_{n=1,3,5..}^{\infty} \bar{p}_n(\eta) \sin(n\pi\xi) \tag{2.24}$$

and

$$-\beta^2 \varepsilon_c = \sum_{n=1,3,5..}^{\infty} a_n \sin(n\pi\xi) \tag{2.25}$$

is selected. This solution automatically satisfies the boundary conditions at $\xi = 0$ and $\xi = 1$, and leads to the differential equation:

$$\bar{p}_n''(\eta) - \frac{\alpha^2 + \beta^2 + n^2\pi^2}{a^2/b^2} \bar{p}_n(\eta) = -\frac{\beta^2}{a^2/b^2} \frac{4}{n\pi} \varepsilon_c \tag{2.26}$$

The solution of this differential equation is:

$$\bar{p}_n(\eta) = A \sinh(\lambda\eta) + B \cosh(\lambda\eta) + \frac{\beta^2}{\alpha^2 + \beta^2 + n^2\pi^2} \frac{4}{n\pi} \varepsilon_c \tag{2.27}$$

where $\lambda = \frac{\sqrt{\alpha^2 + \beta^2 + n^2\pi^2}}{a/b}$. Symmetry requires that $A = 0$ and $\bar{p}_n(\pm 1) = 0$ means:

$$B = -\frac{\beta^2}{\alpha^2 + \beta^2 + n^2\pi^2} \frac{4}{n\pi} \frac{1}{\cosh(\lambda)} \varepsilon_c \tag{2.28}$$

leading to:

$$\bar{p}(\xi,\eta)=\sum_{n=1,3,5,..}^{\infty}\frac{\beta^2}{\alpha^2+\beta^2+n^2\pi^2}\frac{4}{n\pi}\left(1-\frac{\cosh(\lambda\eta)}{\cosh(\lambda)}\right)\sin(n\pi\xi)\varepsilon_c \tag{2.29}$$

The total load, P, is defined by:

$$P=\int_0^a 2\int_0^b p(x,y)dxdy \tag{2.30}$$

which is needed to calculate the compression modulus, E_c. Substituting in Equation (2.29) to Equation (2.30):

$$P=2abK\varepsilon_c\sum_{n=1,3,5,..}^{\infty}\frac{\beta^2}{\alpha^2+\beta^2+n^2\pi^2}\frac{4}{n\pi}\int_0^1\sin(n\pi\xi)d\xi\int_0^1\left(1-\frac{\cosh(\lambda\eta)}{\cosh(\lambda)}\right)d\eta \tag{2.31}$$

Solving the double integral, and since $E_c=\dfrac{P}{2ab\varepsilon_c}$:

$$E_c=8K\sum_{n=1,3,5,..}^{\infty}\frac{\beta^2}{\alpha^2+\beta^2+n^2\pi^2}\frac{1}{n^2\pi^2}\left(1-\frac{\tanh(\lambda)}{\lambda}\right) \tag{2.32}$$

which is the compression modulus of a rectangular pad including bulk compressibility of the elastomer and extensibility of the fiber reinforcement.

From Equation (2.32) with $S=ba/t(2b+a)$ for a rectangular pad:

$$E_c=96GS^2(2+a/b)^2\sum_{n=1,3,5,..}^{\infty}\frac{1}{(\alpha_1^2+\beta_1^2)(2+a/b)^2+n^2\pi^2}\frac{1}{n^2\pi^2}\left(1-\frac{\tanh(\lambda_1)}{\lambda_1}\right) \tag{2.33}$$

and the dimensionless parameters are:

$$\alpha_1^2=\frac{24GS^2t}{E_ft_f}$$
$$\beta_1^2=\frac{12GS^2}{t^2K} \tag{2.34}$$
$$\lambda_1=\frac{\sqrt{(\alpha_1^2+\beta_1^2)(2+a/b)^2+n^2\pi^2}}{a/b}$$

Figure 2.4 shows the sensitivity of E_c to the ratio of *a/b* for $0\le\alpha_1^2\le 10$ with $\beta_1^2=0$ and $\beta_1^2=1$. Note that α_1^2 and β_1^2 are interchangeable in the figure. The effect of bulk compressibility or reinforcement extensibility is pronounced regardless of the ratio of *a/b*.

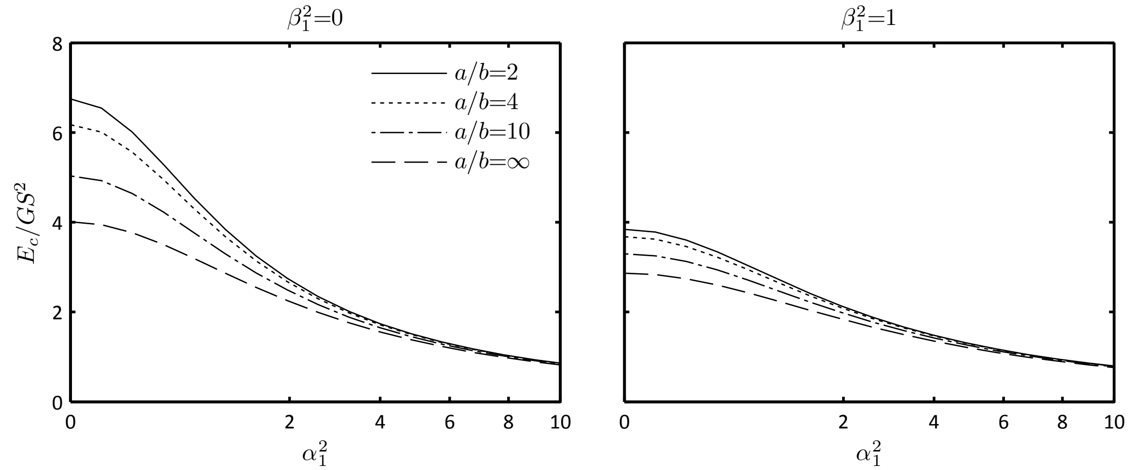

Figure 2.4 **Effect of the *a/b* ratio on E_c for a rectangular pad including elastomer bulk compressibility and reinforcement extensibility.**

2.4 DISPLACEMENTS, FORCE IN THE REINFORCEMENT, AND SHEAR STRAIN

The force in the reinforcement and shear strain in the elastomeric layers may also be of interest to designers, and the closed-form solutions are presented here. Expressions for the displacements and the force per unit length in the reinforcement are derived and expressed as functions of the compression strain. From Equation (2.11), the displacement relating to the lateral bulging can be expressed in terms of the pressure as:

$$u_0 = -\frac{t^2}{8G} p_{,x}$$
$$v_o = -\frac{t^2}{8G} p_{,y} \tag{2.35}$$

Substituting in Equation (2.29) and evaluating the partial derivative, the displacement terms become:

$$u_0(\xi,\eta) = -6a\varepsilon_c \sum_{n=1,3,5,..}^{\infty} \frac{1}{\alpha^2+\beta^2+n^2\pi^2}\left(1-\frac{\cosh(\lambda\eta)}{\cosh(\lambda)}\right)\cos(n\pi\xi)$$
$$v_o(\xi,\eta) = 6\frac{a^2}{b}\varepsilon_c \sum_{n=1,3,5,..}^{\infty} \frac{1}{\alpha^2+\beta^2+n^2\pi^2}\frac{\lambda}{n\pi}\frac{\sinh(\lambda\eta)}{\cosh(\lambda)}\sin(n\pi\xi) \tag{2.36}$$

From Equation (2.19), the displacement terms related to the extension of the fiber reinforcement are:

$$u_{1,x} = v_{1,\mathrm{y}} = \frac{Kt}{E_f t_f}\varepsilon_c \sum_{n=1,3,5,..}^{\infty} \frac{\beta^2}{\alpha^2+\beta^2+n^2\pi^2}\frac{4}{n\pi}\left(1-\frac{\cosh(\lambda\eta)}{\cosh(\lambda)}\right)\sin(n\pi\xi) \tag{2.37}$$

Integrating yields:

$$u_1(\xi,\eta) = -2a\varepsilon_c \sum_{n=1,3,5,..}^{\infty} \frac{\alpha^2}{\alpha^2+\beta^2+n^2\pi^2} \frac{1}{n^2\pi^2}\left(1-\frac{\cosh(\lambda\eta)}{\cosh(\lambda)}\right)\cos(n\pi\xi)$$

$$v_1(\xi,\eta) = 2b\varepsilon_c \sum_{n=1,3,5,..}^{\infty} \frac{\alpha^2}{\alpha^2+\beta^2+n^2\pi^2} \frac{1}{n\pi}\left(\eta-\frac{1}{\lambda}\frac{\sinh(\lambda\eta)}{\cosh(\lambda)}\right)\sin(n\pi\xi) \quad (2.38)$$

With the displacement terms related to the extension of the reinforcement known, the force per unit length in the fiber reinforcement from Equation (2.16) and Equation (2.37) is:

$$F_{xx} = F_{yy} = 2E_f t_f \varepsilon_c \sum_{n=1,3,5,..}^{\infty} \frac{\alpha^2}{\alpha^2+\beta^2+n^2\pi^2} \frac{1}{n\pi}\left(1-\frac{\cosh(\lambda\eta)}{\cosh(\lambda)}\right)\sin(n\pi\xi) \quad (2.39)$$

Note that the expressions for F_{xx} and F_{yy} are identical which implies that at any point the force in the reinforcement per unit length is equal in both perpendicular directions.

The maximum shear strain due to compression, $\gamma_{xz,\max}$ and $\gamma_{yz,\max}$, are important design considerations. By substituting Equation (2.36) into Equation (2.10), the maximum shear strain due to compression can be expressed as:

$$\gamma_{xz,\max} = 24\frac{a}{t}\varepsilon_c \sum_{n=1.3.5,...}^{\infty} \frac{1}{\alpha^2+\beta^2+n^2\pi^2}\left(1-\frac{1}{\cosh(\lambda)}\right)$$

$$\gamma_{yz,\max} = 24\frac{a^2}{tb}\varepsilon_c \sum_{n=1.3.5,...}^{\infty} \frac{1}{\alpha^2+\beta^2+n^2\pi^2}\frac{\lambda}{n\pi}\tanh(\lambda)\sin\left(\frac{n\pi}{2}\right) \quad (2.40)$$

The maximum shear strain due to compression occurs at the interface of the fiber reinforcement and elastomeric layer at the free edge of the pad.

3 Special Case: Square Pad

For the special case of a square pad with $a = 2b$ and $S = a/4t$, Equation (2.32) reduces to:

$$E_c = 1536GS^2 \sum_{n=1,3,5,..}^{\infty} \frac{1}{\alpha^2 + \beta^2 + n^2\pi^2} \frac{1}{n^2\pi^2} \left(1 - \frac{\tanh(\lambda)}{\lambda}\right) \tag{3.1}$$

with the dimensionless parameters:

$$\begin{aligned} \alpha^2 &= \frac{384GS^2t}{E_f t_f} \\ \beta^2 &= \frac{192GS^2}{K} \end{aligned} \tag{3.2}$$

$$\lambda = \frac{\sqrt{\alpha^2 + \beta^2 + n^2\pi^2}}{2}$$

If the elastomer is assumed to be incompressible and the fiber reinforcement is assumed inextensible (i.e., $K \to \infty$ and $E_f \to \infty$) the dimensionless parameters are $\alpha^2 = 0$ and $\beta^2 = 0$, and Equation (3.1) reduces to:

$$E_c = 1536GS^2 \sum_{n=1,3,5,..}^{\infty} \frac{1}{n^4\pi^4} \left[1 - \frac{2}{n\pi} \tanh\left(\frac{n\pi}{2}\right)\right] \tag{3.3}$$

which is identical to the solution for a square pad with an incompressible elastomer and rigid reinforcement presented in Kelly and Konstantinidis [2011].

Similarly, for a square pad with inextensible reinforcement and a compressible elastomer (i.e., $\alpha^2 = 0$) Equation (2.32) becomes:

$$E_c = 1536GS^2 \sum_{n=1,3,5,..}^{\infty} \frac{1}{\beta^2 + n^2\pi^2} \frac{1}{n^2\pi^2} \left(1 - \frac{\tanh(\lambda)}{\lambda}\right) \tag{3.4}$$

which is identical to the solution presented in Kelly and Konstantinidis [2011].

Figure 3.1 shows the compression modulus of a square pad over $0 \le \alpha^2 \le 50$ and $0 \le \beta^2 \le 50$. For the special case of an incompressible elastomer and inextensible reinforcement,

$E_c = 6.748GS^2$. The compression modulus decreases with increasing elastomer bulk compressibility or increasing extensibility of the reinforcement. Note that Equation (3.1) is equally sensitive to changes in α or β. Consequently, Figure 3.1 is symmetric about the plane $\alpha = \beta$, and in the two-dimensional representation, α or β are interchangeable. Note that as either α or β increases that the sensitivity to the other parameter decreases. For example, with $\beta^2 = 0$, $2.060 \le E_c/GS^2 \le 6.748$, which corresponds to a maximum decrease of 69% over the range of α^2 considered if extensibility of the reinforcement is included. Similarly, with $\beta^2 = 50$, $1.250 \le E_c/GS^2 \le 2.060$, which corresponds to a maximum decrease of 39% over the same range of α^2.

The maximum shear strain due to compression for a square pad, γ_{max}, from Equation (2.40) is:

$$\frac{\gamma_{max}}{\varepsilon_c} = 96S \sum_{n=1,3,5,..}^{\infty} \frac{1}{\alpha^2 + \beta^2 + n^2\pi^2}\left(1 - \frac{1}{\cosh(\lambda)}\right) \tag{3.5}$$

Figure 3.2 shows the maximum shear strain due to compression normalized by ε_c over a range of $5 \le S \le 50$. Note that the lower bound of S is determined by the pressure solution, which is considered appropriate for shape factors of 5 and greater [Kelly 1993]. In all cases considered the ratio quickly approaches a horizontal asymptote. The ratio increases with an increase in the *K/G* ratio, as well as an increase in $E_f t_f / tG$.

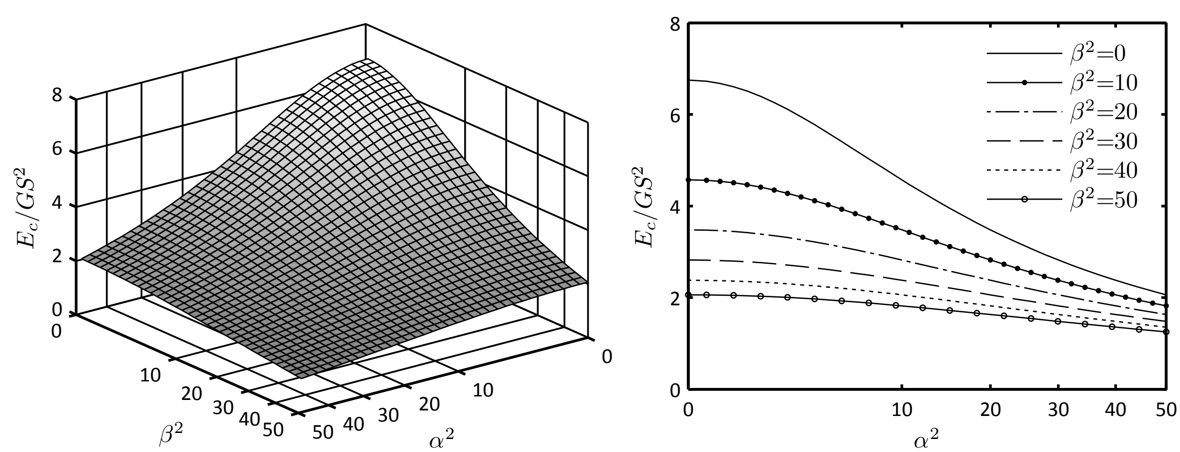

Figure 3.1 Compression modulus of a square pad.

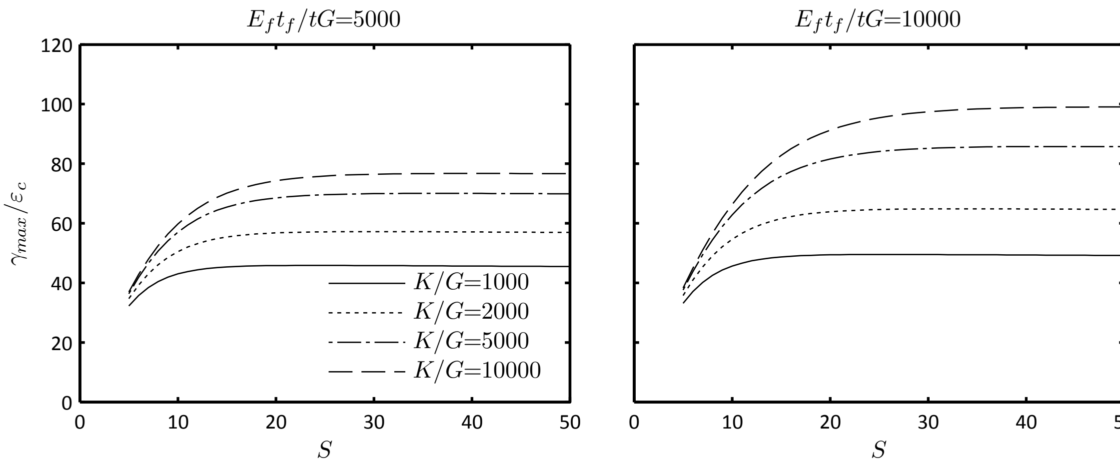

Figure 3.2 **Maximum shear strain due to compression normalized by the compression strain as a function of the shape factor.**

4 Conclusions

Many large urban centers are extremely vulnerable to the damaging effects of large earthquakes. For example, large cities such as Istanbul and Tehran have many thousands of buildings that were built prior to the enforcement of stringent building codes. Buildings in the range of two to six stories have been constructed using only vertical load designs with no provision for horizontal resistance. In many cases these buildings are used as residences, offices, and shops. This magnitude of buildings cannot realistically be demolished and replaced, and retrofitting them by conventional methods would be highly disruptive to the occupants.

Modern methods of structural control would be much too expensive for these buildings, but it is possible that a system of inexpensive seismic isolation could be adapted to improve the seismic resistance of poor housing and other buildings such as schools and hospitals. In at least one retrofit project in Armenia, a large multi-family housing block was retrofitted using rubber isolators with no need for the families to leave while the construction was completed.

Development of low-cost seismic isolators that can be mass-produced by a relatively simplified manufacturing process would stimulate worldwide application of the seismic isolation technology. The development of this technology is appropriate for the retrofit of existing structures with deficiencies and for new construction in lesser developed and developed countries. The recent development of fiber-reinforced elastomeric bearings has the potential of producing bearings that are equally vertically stiff, but cheaper and easier to manufacture than steel-reinforced bearings. A large variety of fiber materials is available, ranging from glass to carbon, and this gives the bearing designer more options. When the idea is to provide a low-cost system with a performance that is close to that of a steel-reinforced bearing, then the use of a high-stiffness fiber-like carbon or Kevlar is required. If a lower vertical stiffness can be tolerated, then a cheaper fiber such as glass can be used.

Fiber-reinforced bearings do not require steel end plates or the elastomeric cover necessary to protect the steel from rusting. Consequently, the bearings will be much lighter than steel-reinforced bearings and can be manufactured as large slabs, and the bearings cut from the slab to the required shape. This report assumed that the optimal shape of the bearing cut from a slab will be rectangular. A single–series solution for the vertical stiffness of a rectangular bearing was presented herein; this solution is computationally efficient and allows a rapid calculation of the stiffness for both design and analysis purposes.

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ISSN 1547-0587X