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CELLULAR PERIODIC MATERIAL DESIGN FOR ENHANCED SEISMIC PROTECTION OF LOW-RISE BUILDINGS

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Abstract

In most recent earthquakes, traditional seismic design demonstrated its effectiveness in reducing casualties through ductile structural mechanisms, but allowed for extensive structural damages that accounted for tremendous economic losses. This evidence raised awareness for the need of an increased level of resiliency, mostly in low-rise buildings. Seismic isolation is a protection system that proved to be successful in prevent damages and maintaining operability. However, high costs and sever testing protocols currently discourage the extensive application of this technology to low-rise buildings. In this study, an architected periodic cellular material with unprecedented characteristic is proposed as a low-cost alternative to traditional technologies to produce seismic isolation devices for implementation in residential, retail and office buildings. Results from preliminary numerical analysis demonstrate the range of performance of this novel architected material in comparison with traditional materials. The scalability of the architected material is also addressed with the aim of investigating the feasibility of using tests on small assemblies of the constituent unit-cells instead of full scale tests to assess the structural performance of the isolators.

Keywords: Seismic isolation; periodic cellular materials; testing protocols; resiliency, low-rise buildings

1. Introduction

Traditional seismic design is aimed at providing sufficient ductility and energy dissipation capacity to prevent structural collapse, but this comes at the cost of structural damages during seismic events and loss of functionality for extended periods of time. Recent earthquakes proved the success of traditional seismic design in reducing casualties, but raised the issue of how much protection should be provided economically and socially to residential houses. In the 1994 Northridge earthquake, damages to residential houses accounted for half of the total direct losses and dramatic social disruption [1]. In the 2011 Christchurch earthquake, around three quarters of the Christchurch housing stock was damaged in an area accounting for 8% of the whole New Zealand GDP, causing immediate financial impact and considerable outflow of residents to overseas destinations [2]. Structural damage prevention, and immediate occupancy after a seismic event, may be pursued through seismic isolation, which is recognized as an effective technique to increase seismic resiliency by absorbing and dissipating most of the ground shaking vibration energy at the isolation interface, thus preventing this energy from affecting the structure [3, 4, 5]. Despite their effectiveness being recognized and supported by design procedures in current building standards [6, 7], seismic isolation systems are expensive and still being almost exclusively adopted for enhanced protection of strategic/high-rise buildings and critical infrastructure. Extensive use of seismic isolation for low-rise residential buildings would have a tremendous impact on mitigating the socio-economic consequences of major seismic events. In the traditional structural design, the sizing of structural/mechanical components for a given loading scenario is based on the properties of the constituent material.

Direct cost reduction is one of the key factor for increasing seismic isolation attractiveness for low-rise buildings, as demonstrated by recent research efforts on the subject [8]. Direct costs are nowadays severely affected by state-of-practice manufacturing process and production quality assessment. A suitable seismic isolator must possess the following features: (i) high axial stiffness and bearing capacity in vertical direction, (ii) high flexibility in lateral direction, (iii) large lateral displacement capacity, and (iv) high energy dissipation capacity under lateral deflection. These design features are currently pursued by incorporating dissimilar materials with extreme performance characteristics (e.g. large shear deformability, low and stable coefficient of friction) into compact devices, thus requiring expensive and delicate manufacturing processes. Although several concepts have been proposed, isolation devices currently used for passive vibration control of civil structures are practically limited to steel reinforced rubber bearings [9, 10, 11] and sliding pendulum bearings [12, 13], thanks to their relative cost-effectiveness and reliability.

With the advancement of design, manufacturing, and optimization of architected materials, an array of additional degrees of freedom are introduced in the design. Cellular materials with architectures (architected material) are obtained by introducing architected/engineered open structures into solid materials [14]. The mechanical properties of cellular materials can be tailored through an optimal design of the spatial configuration of voids and solids (cellular architecture) for a given solid constituent [15]. Manufacturing approaches, advanced experimental tools, numerical models, and optimization strategies for cellular materials, obtained as periodic reproduction of a unit cell (periodic cellular material) have been extensively investigated [15, 16, 17]. In [18] it is demonstrated that the employ of periodic cellular materials can simplify the analysis and prediction of the mechanical behavior of the entire assembly. Periodic cellular material aimed at increasing energy absorption of a structure has been recently designed and successfully manufactured [19].

The design phase for these materials is shifted from the structural component scale to the material scale. Mechanical properties of the architected materials can be optimized to limit sizes, simplify shapes and reduce costs of the structural components. The aim of this paper is to investigate the feasibility of designing materials for seismic isolation of civil structures. A novel class of architected materials is presented. The proposed architected material has unprecedented characteristics of lateral flexibility, vertical bearing stiffness, and energy dissipation capability, which may foster the application of seismic isolation beyond the limits set by current technologies.

2. Research significance

The proposed architected material is designed to have seismic isolation properties that can be optimized for a wide range of applications. The use of a low-cost manufacturing process makes this material affordable, and may foster application of seismic isolation to low-rise buildings, and raise their level of seismic protection to levels so far achieved mostly by critical buildings and infrastructure. Buildings' owners will benefit from enhanced safety, reduced repair costs, and extended operability after earthquakes. Large-scale use of this technology will enable communities to become more resilient to earthquakes, and reduce social and economic impacts of seismic events.

3. Target material properties

Depending on the specific application, different performance characteristics may be required for the seismic isolation material. Common features for all the isolators are high vertical stiffness, bearing strength and lateral flexibility, large lateral deformation capacity, and energy dissipation capability. At the material scale, these properties may be obtained through an elastic vertical behavior, associated with the Young's modulus E, and an elastic shear behavior, characterized by the shear modulus G, followed by a plastic behavior, governed by a plastic shear modulus G_p until the ultimate shear strain is reached. These parameters are used to design the architected material for seismic isolation application.

The pressure transmitted from the isolated structure (i.e. 2-20 MPa for civil structures) to the isolators defines limits on the vertical bearing capacity of the isolators. Safety standards often define limits on maximum vertical displacements of the structure under vertical load. These requirements call for a stress-strain performance of the architected material in the vertical direction characterized by high Young's modulus in the range, E=10 to 60 GPa, spanning from the modulus of common wood and that of concrete materials (see Fig. 1).

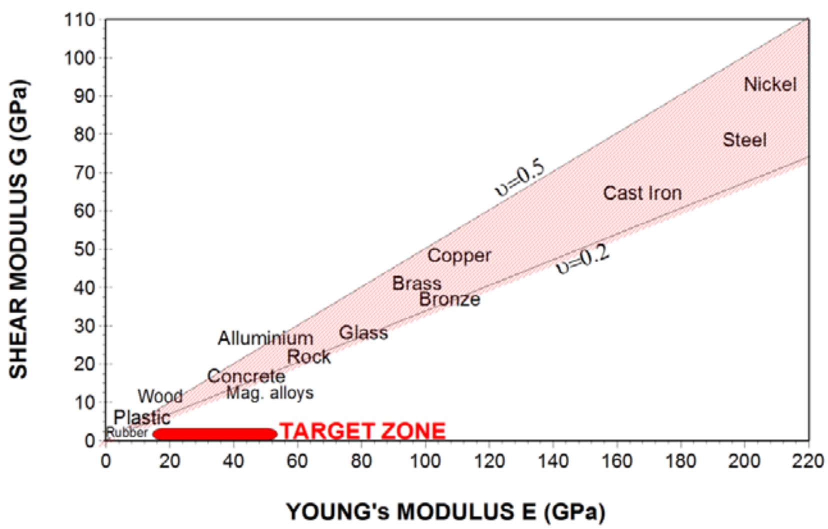

Fig. 1 – Shear modulus versus Young Modulus for traditional existing materials and target area

While bearing vertical loads, isolators need to avoid lateral movements for low vertical loads (e.g. wind loads) and accommodate high lateral displacements for seismic loads. Safety standard often define limits on the horizontal stiffness of the isolators. These requirements call for a stress-strain performance of the architected material in the horizontal direction characterized by moderate shear modulus (G<10 GPa) for low lateral forces, followed by a low shear modulus (G<0.1 GPa) in the range of common elastomeric materials and a large shear strain capacity (γ up to 2.00) when a threshold lateral force is exceeded. The higher the shear strain capacity, the lower the thickness of the isolator is for a given displacement demand.

Architected materials obtained as replication of truss cells have been already developed to allow a variety of combination of elastic properties such as E, and G. However, these materials are designed to have an elastic behavior and cannot accommodate large shear strain. The energy dissipation capacity is required of the isolators in case of high level of seismic load (damping ratio between 0.05 and 0.40).These requirements call for a material with high energy dissipation capability or ductility.

In this paper cellular architecture and suitable constituent solid materials are combined using known structural engineering principles in order to design a periodic cellular material that can be used for the seismic protection of structures.

4. Material design

A three-dimensional organized cellular material (Fig. 2) made of a plurality of unit cells is designed to exhibit distinct mechanical response with directionally dependent behavior. Specifically, the ability to independently tailor mechanical response in the vertical and horizontal direction is obtained through the design of a unit cell made of different sub-constituents.

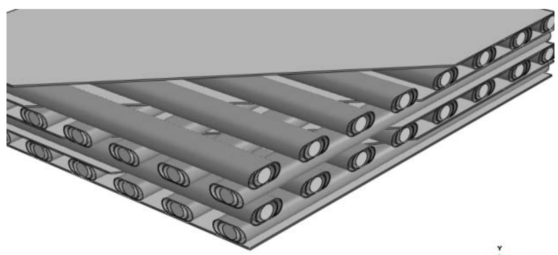

Fig. 2 – Assembly of unit cells in layers with different directions

Each layer of the material is composed by a periodic assembly of unit cells oriented in a given direction. By alternating layers with different orientations (at least in two perpendicular directions), the material can stretch with different properties in different lateral directions. The sample unit cell (Fig. 3) includes a core that is free to roll inside a cylindrical shell. The top and the bottom of the cylindrical shell are connected to an upper plate and a bottom plate through the shell's segments of length (*a*). Vacuum-brazing can be used to create these connections for steel materials. The thickness of the upper and lower plates should be designed to ensure their essentially rigid response upon deformation. The length (*L*) of the rigid plates corresponds to the horizontal distance on center between the cells in the assembly.

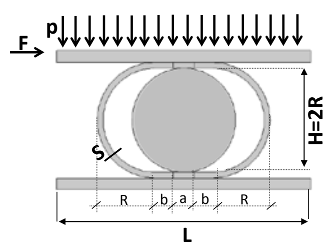

Fig. 3 – Typical constitutive unit cell subjected to vertical loads and shear

For implementation in seismic isolators, the Shear Modulus (elastic and plastic) and Young's Modulus are the most important properties of the architected material. Because the internal core is free to roll, it provides the cellular material with high vertical stiffness and bearing capacity, but low horizontal stiffness. The cylindrical shell provides the restoring force associated with the horizontal stiffness and energy dissipation capacity through shearing strain under large horizontal displacement.

By varying the cellular architecture parameters (length of the plate *L*, radius of the core *R*, and thickness of the shells *s* a wide range of Young and Shear modulus can be achieved while using the same constituent material, as shown in the next paragraph.

5. FEM simulation

In order to investigate the behavior of the architected material under vertical compressive and lateral loads, a finite element analysis taking into account material and geometric nonlinearities is performed on a representative unit cell. The sub-elements plate, shell and core of Fig. 3 are simulated in ABAQUS with 3D solid elements. A unit width t of the cell is assumed. A steel material with Young's modulus E=200GPa and yield strength σ_y=500MPa is used for all the elements. The stress-strain behavior is assumed elastic perfectly-plastic. A surface contact with friction coefficient of 50% is used between the sub-elements. The value of the coefficient of friction is representative of low-boundary friction conditions between steel elements.

Rotational DOFs of top and bottom plates are fixed to simulate the shear-type behavior of a multi-layer assembly. A vertical pressure is applied to the top plate, then a lateral deflection is imposed in displacement control, resulting in shearing stresses up to 20%-30% the vertical stress. These loads reproduce typical stresses induced by design earthquakes into seismic isolators.

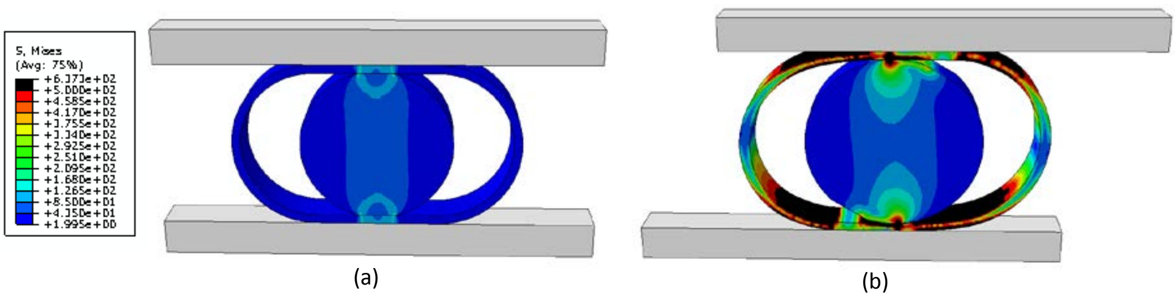

Fig. 4 – Example of unit cell with L=10 mm, R=2 mm, and s=0.2 mm loaded with a vertical pressure of 10MPa: (a) Von Mises stress distribution of the cell under vertical load at shear strain γ=0 (maximum value of von Mises stress is 203MPa); (b) Von Mises stress distribution of the cell under vertical load and shear strain γ=0.5

The proposed architected material is expected to behave elastically during application of the vertical load, while it deforms plastically as the lateral deflection increases. For example the unit cell in Fig. 4 is in the elastic range under the design vertical load and enters the plastic range when the shear strain reaches the value of 0.1.

Assuming a simplified bilinear shear stress-strain diagram for the architected material in lateral direction, the elastic shear modulus G and plastic shear modulus G_p are expressed by:

$$G = \frac{F_y}{d_y}\frac{H}{A} \tag{1}$$

$$G_p = \frac{(F_u - F_y)}{(d_u - d_y)}\frac{H}{A} \tag{2}$$

where F_y and F_u are the yielding and ultimate force, d_y and d_u are the yielding and ultimate displacement of the unit cell, H is the height of the unit cell and A=tL is its in-plan area, with t being the width of the unit cell.

A parametric analysis is performed on the unit cell, for a set of shell thickness values (s_1=0.1 mm, s_2=0.2 mm, s_3=0.4 mm), a set of plate length values (L_1=5 mm, L_2=10 mm, L_3=20 mm), and two different types of internal core (full and hollow sections). The total height of the cell H is assumed equal to 4 mm. The resultant set of values for Young's Modulus and plastic shear Modulus of the material are shown in Fig. 5.

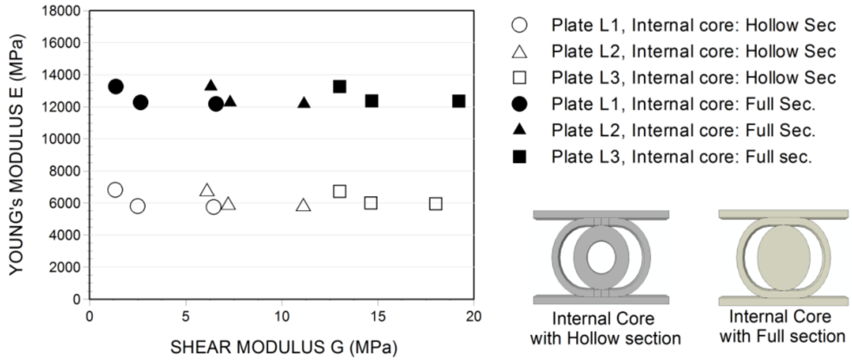

Fig. 5 – Young's Modulus and Shear Modulus of the architected material

Based on the results of the numerical analysis, the Young's Modulus appears significantly affected only by the geometry of the internal core. The Shear Modulus, instead, is sensitive to the length of the plate (*L*), the thickness of the shells (*s*), and the radius of the shell (*R*). The variability of the Sear Modulus with these parameters is represented in Fig. 6. A simplified analytical formulation for the Shear Modulus is proposed in the next paragraph.

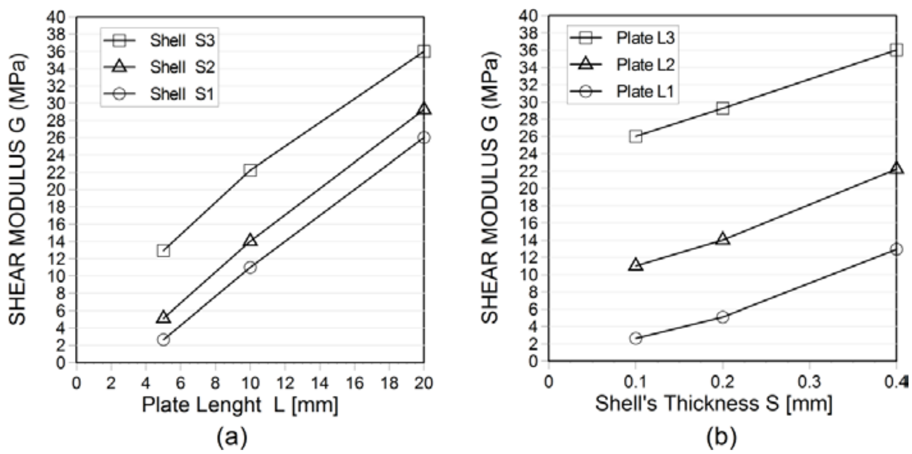

Fig. 6 – Shear Modulus of architected materials as a function of (a) plate length and (b) shell thickness

6. Analytical formulation

A simplified analytical formulation was developed and validated upon results from the nonlinear finite element analysis. The geometric parameters required to fully define the unit cell are the cell size *L* (length of the plate), the radius of the core *R*, and the shell thickness *s*. In non-dimensional form, the geometric parameters are expressed as L/s and R/s.

For small value of shell thickness respect to the radius of the core $s/R \leq 0.05$, the vertical load $W=pLt$ is assumed to be resisted by the internal core. The lateral force is resisted by the rolling friction of the internal core and the shearing of the shells. For steel to steel contact the rolling friction force is assumed negligible with respect to the shell forces. As a consequence, the vertical and lateral force resisting systems may be analyzed separately. The shell is analyzed as a lateral system subjected to a horizontal force (*F*), while the internal core is analyzed as a subjected the vertical load (*W*) only.

Based on these simplifying assumptions, the shell is analyzed as two symmetric arches bounded at the extremities as shown in Fig. 7. An elastic-perfectly plastic circular arch of length *L* and radius *R* when subjected to a lateral horizontal concentrated load *F*, begin to yield in the maximum stressed sections, which are located at the top and bottom of the arch. The analytical shear/stress strain diagram and corresponding elastic and plastic shear modulus of the architected material can be derived from the bilinear force displacement diagram of the unit cell (Fig. 8), once the yield and ultimate lateral forces F_y and F_u, and yield and ultimate lateral displacements d_y and d_u, are determined.

Given the yield moment M_y per unit of length of the arch of height H, the yielding load F_y is given by:

$$F_y = \frac{M_y}{H/2} \tag{3}$$

The yield shear stress τ_y of the architected material can be expresses as a function of the yield stress of the constitutive material and the geometric parameter *s/R* and *s/L* of the unit cell:

$$\tau_y = \frac{\sigma_{yc}}{3}\left(\frac{s}{R}\right)\left(\frac{s}{L}\right) \tag{4}$$

where σ_{yc} is the stress at yielding of the constitutive material, while b and s are the sizes of the section. The force at yielding F_y obtained with the analytical formulation is compared with the FEA model for different values of shell thickness s and radius R in Fig. 9. The variation of the shear stress τ_y with the geometric parameter of the unit cell is shown in Fig. 10.

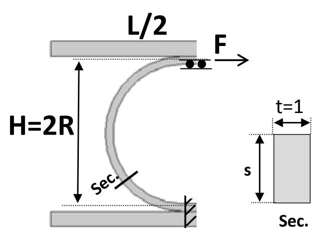

Fig. 7 – Geometry, load and boundary condition of the arch

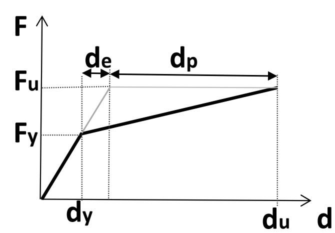

Fig. 8 – Bilinear force displacement diagram of the unit arch

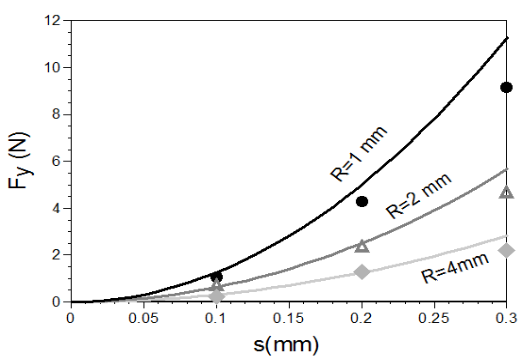

Fig. 9 – Force at yielding evaluated with the simplified analytical formulation vs numerical solution for different values of radius and thickness

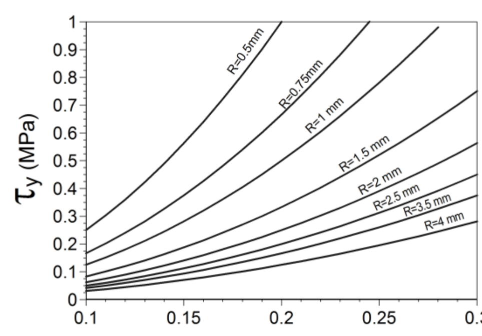

Fig. 10 – Variation of the shear stress at yielding of the architected material with the geometric parameter R and s of the unit cell

The shear modulus of the architected material is also expressed as a function of the Young's modulus of the constitutive material E_c, and the geometric parameters of the unit cell *s/L* and *s/R*:

$$G = \frac{E_c}{2}\left(\frac{s}{L}\right)\left(\frac{s}{R}\right)^2 \tag{5}$$

In order to evaluate the ultimate capacity of the architected material after yielding, a plastic analysis of the unit cell is performed. Assuming a bilinear elasto-plastic behavior of the constitutive material, the circular arch of mean radius *R* when subjected to a horizontal load *F* begins to collapse plastically after two hinges have been formed at the top and bottom of the arch. The lateral load that causes a fully plastic bending moment per unit length of the shell is:

$$F_P = \frac{M_P}{H/2} \tag{6}$$

The plastic shear stress τ_p of the architected material can be expressed as a function of the geometric parameter *s/R* and *s/L*:

$$\tau_p = \frac{F_p}{A} = \frac{\sigma_{yc}}{2}\left(\frac{s}{R}\right)\left(\frac{s}{L}\right) \tag{7}$$

where σ_{yc} is the yielding stress of the constitutive material. The plastic shear modulus G_p, defined by the plastic shear stress τ_p and strain γ_p, is obtained from the force/displacement diagram of the unit cell as:

$$G_p = \frac{\tau_p}{\gamma_p} = \frac{(\tau_u - \tau_e)}{(\gamma_u - \gamma_e)} = \frac{H}{A}\frac{(F_u - F_e)}{(d_u - d_e)} \tag{8}$$

where *A*=*bL* and *H* are the area and height of the unit cell, respectively. Assuming a plastic hinge length L_p=*H/6*, the plastic shear modulus G_p was computed. The analytical shear stress/strain diagram of the arch is compared with the FEM simulation for different values of *R* and *s* in Figs. 11 and 12.

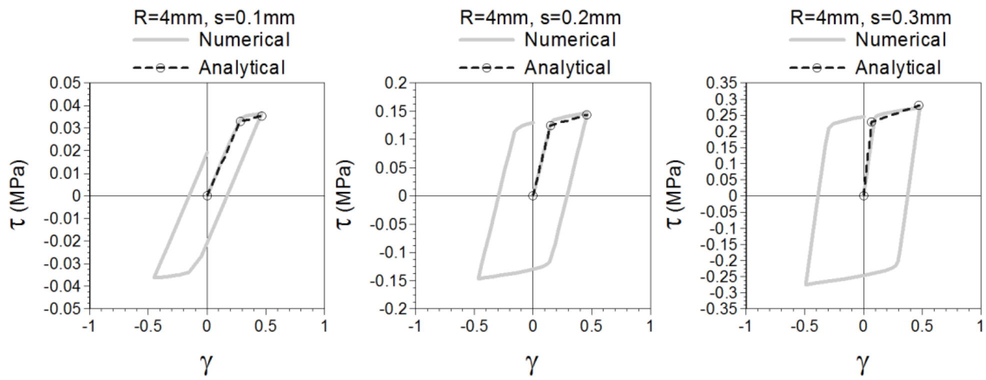

Fig. 11 – Analytical and numerical shear stress/strain diagram of unit cell with *L*=10 mm, *R*=4 mm, *s*=0.1, 0.2 and 0.3 mm. Maximum shear strain γ equal to 0.5

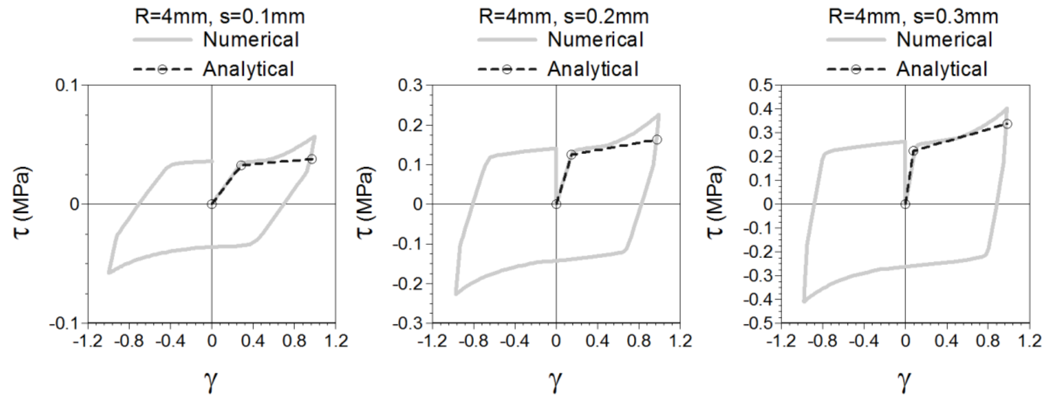

Fig. 12 – Analytical and numerical shear stress/strain diagram of unit cell with L=10 mm, R=4 mm, s=0.1, 0.2 and 0.3 mm. Maximum shear strain γ equal to 1

The analytical formulation is able to predict with good accuracy the linear elastic behavior of the architected material, but fails in predicting the nonlinear behavior. The reason of the divergence between the plastic behavior from the analytical formulation and the numerical analysis is mostly associated with nonlinear geometric phenomena. Due to the high level of lateral displacement, the architected material undergo very large deflections. The shells of the constitutive unit cell experience a transition from the predominant flexural behavior to a predominant axial behavior. This transition causes a hardening effect, which is more evident as the level of shear strain γ increases. The study of the mentioned geometric nonlinearities requires further investigation. The inclusion of these nonlinearities in the predictive model will produce an analytical formulation that can be effectively used for the design of the architected material geometry through optimization procedures. It will also enable a reliable prediction of the nonlinear behavior of the proposed material, for implementation into lumped models for seismic structural analysis.

7. Case study

The analytical formulas were used to design the architected material for the seismic isolation of a simple case study. The architected material is applied to a typical single-family two-story wood house, as shown in Fig. 13. The house has a total plan area of 122 m^2 (1310 ft^2), and a total height of 8.15 m (26.75 ft) at the roof ridge. The total seismic weight of the house is 1605 kN (360 kips). A seismic isolation layer is provided in order to have a minimum vibration period T=3s. For this purpose, an effective lateral stiffness K_{eff}=718 kN/m (as defined in [7]) is required at a peak shear strain γ=1.50, which corresponds to an effective shear modulus G=0.12 MPa, well below the values that can be possibly achieved with rubber isolators. In order to obtain such isolation properties, a radius R=4 mm, and a shell thickness of s=0.2 mm are used. The total length of a single unit cell is 20 mm, and each layer is 10 mm high. A total number of 10 layers are used for the each material pad, whose total depth is 100 mm. The material pads are located underneath the 1st floor at the junctions between beams, and have a total area of 6000 cm^2. The average pressure on the pads is 2.7 MPa.

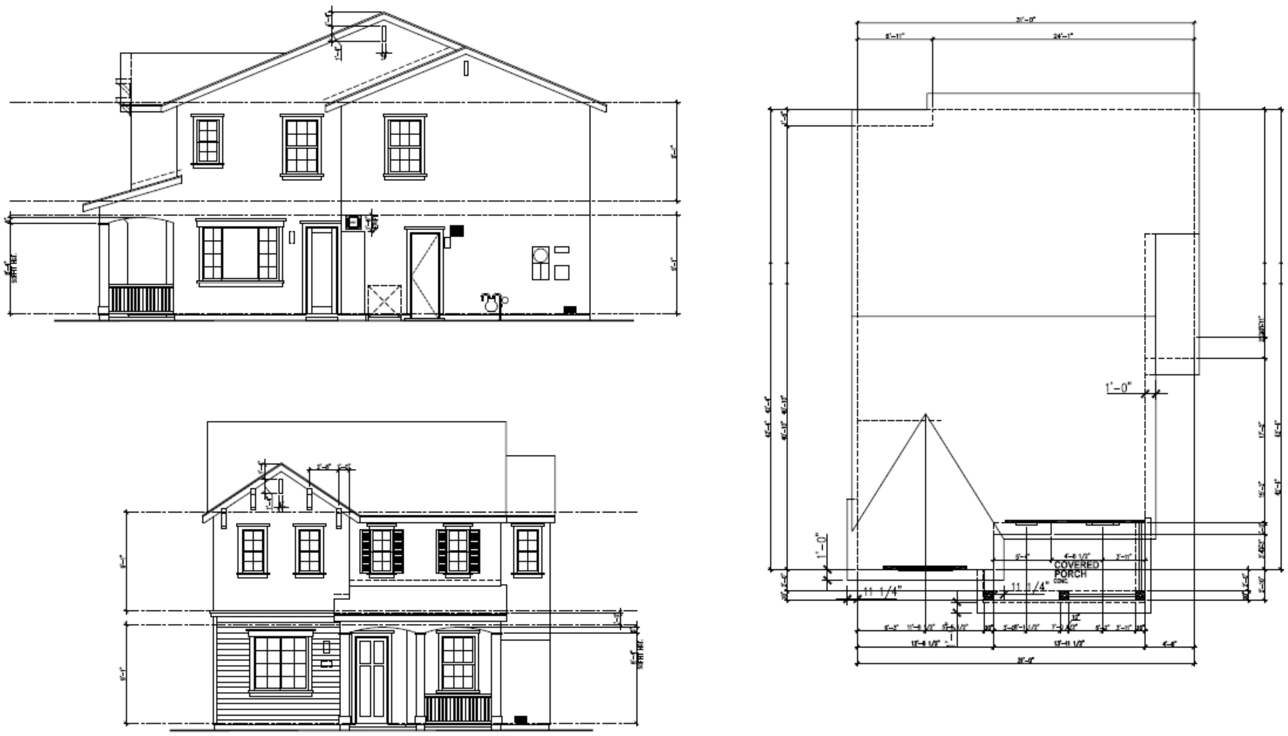

Fig. 13 – Single-family two-story wood house

A nonlinear time-history analysis is performed in order to assess the performance of the isolated structure under a bi-directional input. With this aim, the lateral components of acceleration at the Erzincan station of the 1995 Erzincan earthquake (M_W=6.7, PGA=0.50 g, PGV=64.3 cm/s, PGD=21.9 cm/s) are used. A state-of-the practice SAP 2000 © model is used. The material properties are implemented through nonlinear lumped link elements with kinematic plastic behavior. The resulting displacement pattern at the isolation level and force-displacement loops in longitudinal direction are shown in Fig. 14.

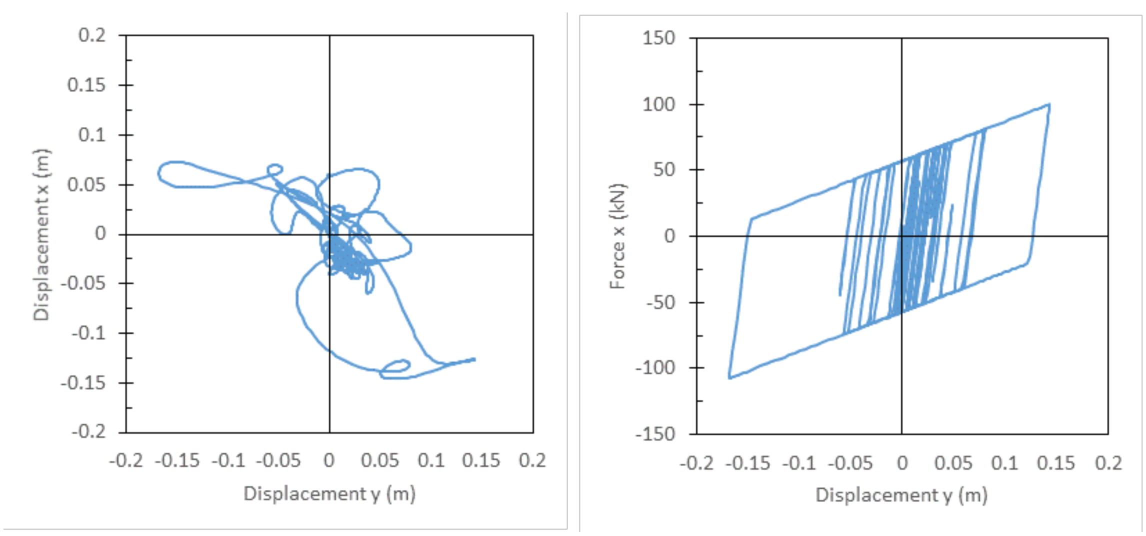

Fig. 14 – Displacement pattern and force-displacement loops

The peak displacement of the isolation plane is 168 mm, related to a peak shear strain of 1.64. The peak base shear is 108 kN, which is approximately 6.7% of the seismic weight of the house. The largest inter-storey drift of 58 mm is detected at the second level, which is approximately 2.1% of the storey height, below the admissible 2.5% limit of the ASCE 7-10. With the limitations associated with use of only one simple case study, the analysis is a preliminary assessment of the efficacy of the architected material as a seismic isolation layer for low-rise buildings.

7. Conclusion

This paper shows the feasibility of designing periodic cellular materials with mechanical properties tailored for seismic isolation application. The great benefit of having seismic isolation layers made of periodic cellular materials is that their seismic performances can be optimized at the material level through the sizing/geometry optimization of the unit cell. The use of cellular materials greatly increases the flexibility in the choice of the isolators' properties in order to satisfy design requirements. Devices made of cellular materials have unprecedented combinations of mechanical properties, which can foster extensive applications to seismic isolation. Seismic isolators made of the new material can be designed in order to meet seismic requirements. This study is a preliminary attempt of investigating the use of architected material for seismic isolation of low-rise buildings. The use of the architected material on a single-family two-story wood house proved effective in reducing lateral forces to 6.7% of the seismic weight, and inter-story drift below limits from current standards. The results of this study are limited to a single house typology. Further experimental and numerical investigations are envisioned in order to verify the effectiveness of the proposed isolation system in comparison with traditional seismic design, and most recent vibration control technologies.

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