LIMIT STATE DOMAIN OF HIGH DAMPING RUBBER BEARINGS IN SEISMIC ISOLATED NUCLEAR POWER PLANTS

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ABSTRACT

The paper describes the work performed at Politecnico di Milano in the field of seismic isolation of nuclear power plants buildings. Within this activity, the development of reliable and efficient FE models in ANSYS® has been pursued along with the definition of a limit state domain for first damage in High Damping Rubber Bearing (HDRB) devices. The paper is settled into a wider procedure aiming at providing a reliable, effective and robust method to evaluate the seismic fragility of base isolated nuclear power plants.

INTRODUCTION AND SCOPE

This work is framed into the research activity performed at Politecnico di Milano within the field of seismic isolation of NPP (Nuclear Power Plant) buildings, with specific attention to the IRIS™ project (International Reactor Innovative and Secure™), a medium size pressurized water reactor under development by an international consortium [1]. The work presented here is part of a procedure described by F. Perotti et al. [2], proposing an innovative approach for the evaluation of seismic fragility for isolated buildings, based on the following steps:

- step 1: performance of laboratory tests on high damping rubber and HDRB isolating devices;
- step 2: development of a reliable and efficient isolator FE model, taking into account all significant sources of mechanical and geometrical nonlinearities; the model, after having been validated against experimental data, will be used to simulate additional and more complex numerical tests;
- step 3: FE model calibration based on laboratory tests;
- step 4: statement of the limit state condition for the isolator, expressing the interaction between horizontal and vertical load at first damage and failure;
- step 5: performance of the fragility analysis for the isolation system.

A first set of laboratory tests on 1:2 scale HDRB devices designed for IRIS™ NPP was performed by ENEA and CIRTEN at CESI-ISMES [3] (Bergamo, Italy) and FIP Industriale S.p.A [4] (Padova, Italy) laboratories, in June 2010. The test results, integrated, where necessary, with experimental data from the literature, were analyzed in order to define the future experimental test campaign required to accomplish step 1, and to tune the analytical and numerical models of HDRB devices.

In a previous work by this research group [5], a robust procedure for developing a FE model of a HDRB device, properly tuned on experimental data, was addressed. The most suitable element type, mesh refinement and analysis control parameters were identified and verified by comparing numerical results to laboratory tests.

In the present paper, the development of a new FE model of a HDRB device has been pursued in ANSYS®, mainly aimed at the definition of a reliable limit state domain under seismic excitation, which represents step 4 in seismic fragility evaluation procedure. A comprehensive study of the global and local behaviour of numerical and analytical models is first presented, under the hypothesis of fully incompressible rubber material. Delamination damage condition is then accounted by Yen-Caiazzo limit state domain [12][13], tuned to rubber tensile strength provided by the manufacturer and maximum tangential stress taken from experimental tests under vertical load [4]. First damage domain is finally addressed, in terms of HDRB global actions, by means of combined FE modelling and analytical treatment.

HDRB DEVICE PROPERTIES AND LABORATORY TESTS

Geometrical data for the IRIS™ designed HRDB device were taken from [4] and are listed in Tab. 1. Mechanical properties were retrieved from experimental tests performed by ENEA on 1:2 scale devices [4] and from the analysis of a set of literature experimental tests on rubber specimens [6][7][8][9]. Mechanical parameters are then used to calibrate the rubber constitutive law by means of a fitting procedure, performed in ANSYS® environment [10].

	full scale	1:2 scale	
Isolator external diameter	1000	500	[mm]
Design vertical load	8000	2000	[kN]
Steel reinforcing plate diameter	980	480	[mm]
Thickness of the internal steel plates	4	2	[mm]
Number of elastomeric layers	10	10	[ ]
Thickness of one elastomeric layer	10	5	[mm]
Total rubber thickness	100	50	[mm]
First shape factor	24	24	[ ]
Second shape factor	9.6	9.6	[ ]
Dynamic shear modulus (at 100% def.)	1.4	1.4	[MPa]

Tab. 1: Full scale and 1:2 scale HDRB parameters

Six 1:2 scale isolators were tested in two sessions. The first [3] comprised vertical loading tests, quasi-static horizontal loading tests and dynamic horizontal loading tests. The second [4], also aimed at investigating isolator failure, comprised a vertical loading failure test and a horizontal quasi-static loading failure test.

Tests showed a vertical failure mode consisting in a radial expulsion of internal steel plates and rubber (Fig. 1b). Horizontal failure occurred during the second cycle at 350% deformation, when the external rubber cover suddenly broken, revealing the failure due to the partial detachment of an internal plate (Fig. 1a).

(a)


(b)


Fig. 1: Horizontal (a) and vertical (b) loading HDRB failure tests

Since no experiments had been already performed to determine actual rubber properties, an analysis of three standard experimental test curves (Uniaxial Tension: UT, Biaxial Tension: BT, Pure Shear: PS) was performed on literature data [6][7][8][9], for different G* shear moduli. The analysis identified similar experimental curves by scaling each case by corresponding G* ratio. Thus G* = 1.4 MPa rubber tests were generated by scaling literature rubber tests. The Simple Shear (SS) test has been obtained from horizontal loading test on 1:2 scale isolators.

HDRB STRESS ANALYSIS

Constitutive law and hyperelastic parameters assessment

In a previous study performed by this research group [5], Ogden, Mooney-Rivlin and Polynomial hyperelastic constitutive laws for elastomeric materials were analysed by an analytical and numerical HDRB model, in order to identify the most promising law in reproducing experimental behaviours. Benchmarks identified the Polynomial 2-Parameters (POLY-2P) constitutive law as the most suitable model for the scope. The present study confirmed previous results, for a different HDRB geometry, in terms of quality of simulation of the HDRB experimental behaviour. Elastic potential function for POLY-2P is reported eq. 1:

$$W = \sum_{i+j=1}^{2} c_{ij} (\bar{I}_1 - 3)^i (\bar{I}_2 - 3)^j + \sum_{k=1}^{2} \frac{1}{d_k} (J - 1)^{2k} \tag{1}$$

c_{10}, c_{01}, c_{02}, c_{20} and c_{11} parameters depend on the actual material, while the volumetric part (d_1 and d_2) is ignored in fulfilment to the hypothesis of fully incompressible rubber. Parameters have been evaluated by fitting laboratory rubber specimen curves quoted in the previous paragraph. Four fitting combinations (Tab. 2) have been defined by including different experimental tests in the fitting procedure, in order to evaluate the stability and convergence sensitivity of the constitutive law. Convergence and accuracy tests were performed by comparing numerical and analytical solutions with the experimental curves, in terms of global reactions. Fitting combination 301 has been identified as the most suitable and will be assumed in all subsequent analyses.

FITTING	TESTS				POLY-2P PARAMETERS [MPa]						
	UT	BT	PS	SS	c_{10}	c_{01}	c_{20}	c_{11}	c_{02}	d_1	d_2
301	**x**	**x**	**x**	**x**	**7.97E-01**	**-5.91E-02**	**1.61E-02**	**-5.29E-03**	**1.10E-03**	**-**	**-**
302	x	-	x	x	-8.99E-01	1.72E+00	-1.46E-01	8.85E-01	-7.30E-01	-	-
303	x	x	-	x	6.84E-01	8.82E-02	3.80E-02	-6.90E-02	1.42E-02	-	-
304	-	x	x	x	1.40E+00	-4.10E-01	-7.22E-02	8.38E-02	-1.10E-02	-	-

Tab. 2. Fitting combinations for Polynomial 2P hyperelastic constitutive law

Numerical model

A parametric FE model of the full scale HDRB was assembled according to geometrical properties listed in Tab. 1 and to the following criteria (Fig. 2):

- *Finite elements*. SOLID185 element for bricks (linear 3D 8-nodes element with 3 DOF at each node, with hyperelasticity, large deflection and large strain capabilities; allowing a mixed formulation for simulating deformations of fully incompressible hyperelastic materials). The integration method is the Uniform Reduced Integration with hourglass control. SHELL281 for steel shell elements (4+4 nodes element with 3+3 DOF at each node, allowing for finite membrane strains); overall number of DOF is about 220’000;
- *Constraints.* At top and bottom face a 20 mm steel plate has been modelled as a node with a rigid link to the corresponding rubber disc; at each steel-rubber interface, the connection between the upper and lower nodes and rubber surfaces is provided by means of node-to-node rigid links;
- *Material*. POLY-2P hyperelastic constitutive law has been adopted (Tab. 2, fitting combination 301);
- *Boundary conditions and loads*. Boundary conditions and loads act at top and bottom nodes. The horizontal action is applied as an imposed horizontal displacement in x direction. Bottom node is always fixed, while upper node constraint prevents displacement along y and all rotations.

The global response of the model was investigated by comparing the numerical solution with experimental results, for the following cases:

- vertical load up to 80’000 kN (Fig. 3b): the agreement is poor since compressibility was not included;
- horizontal displacement up to 350% of the rubber thickness (0 kN and 80’000 kN vertical load, Fig. 3a): there is a good agreement between the experimental and the numerical solution which confirm POLY-2P constitutive model ability to reproduce the HDRB global behaviour, when properly tuned; moreover, vertical load does not affect the horizontal stiffness, mainly due to the HDRB high second shape factor.

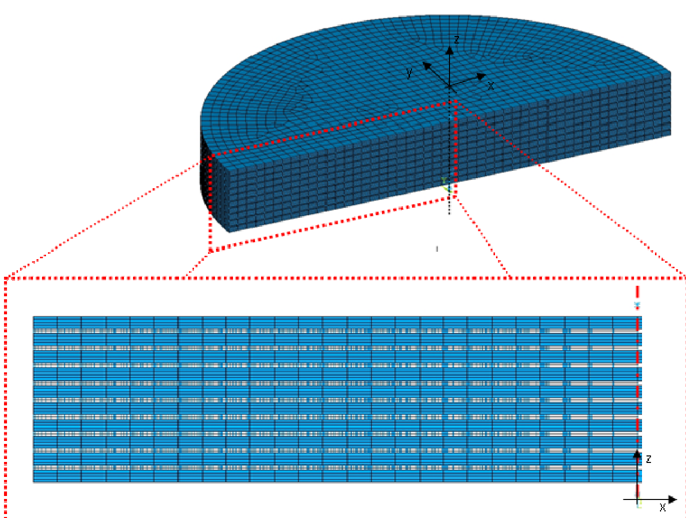
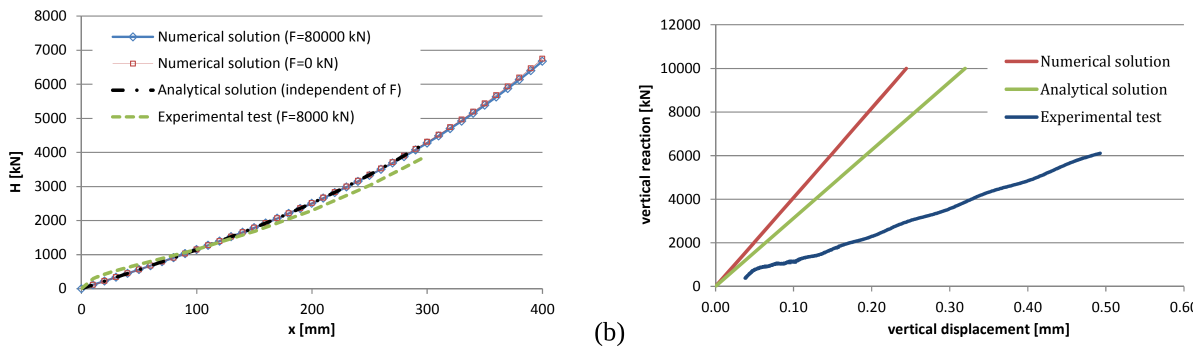


Fig. 2. HDRB FE model. Approximate number of DOFs: 220’000

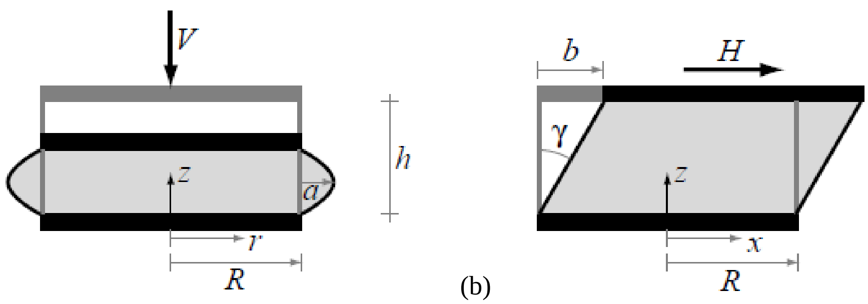


(a) (b)

Fig. 3: Numerical, analytical and experimental HDRB horizontal (a) and vertical (b) stiffness

Analytical model

Corradi et al. [11] proposed two approximate analytical solutions for a single rubber layer subjected to vertical load (linear elastic incompressible material, small displacements), and to horizontal displacement (hyperelastic incompressible material, large displacement), as shown in Fig. 4. The two solutions, applied also in [5], are here further developed in order to reproduce the stress distribution evaluated by numerical FE analyses. The main purpose is to obtain a reliable analytical solution to assess an analytical limit state domain.



(a) (b)

Fig. 4: Single rubber layer analytical solutions scheme. (a): vertical load; (b): horizontal displacement

In terms of stresses induced by vertical load, the Corradi model shows a good agreement with the numerical solution (Fig. 5a, Fig. 6a). In terms of stresses induced by horizontal displacements, on the other hand, the Corradi model introduces an artificial constraint on displacement along the *z*-axis, thus the vertical resultant is not necessarily zero. Comparing the behaviour of the numerical FE solution for HDRB device and the analytical solution for single rubber layer it can be noted that:

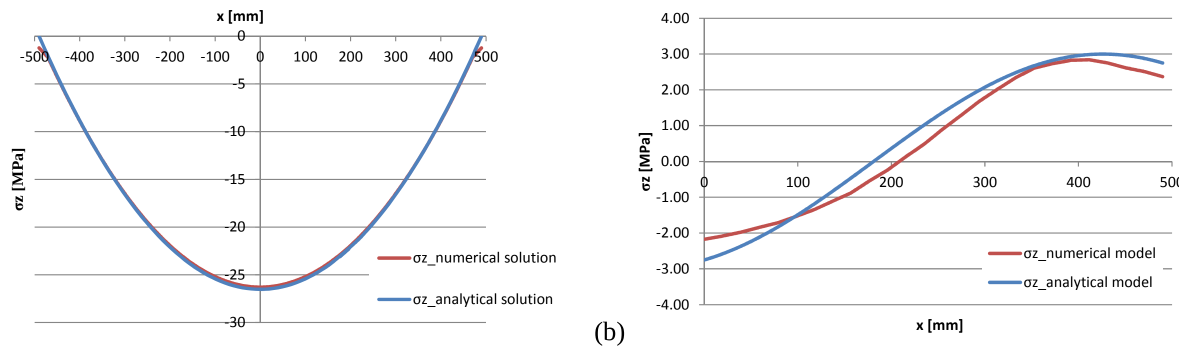
- the shear stress (Fig. 6a and b) does not depend on the interaction among layers: all layers of the isolator can be modelled as individual single rubber layers. Corradi analytical model is thus in good agreement with numerical results;
- the Corradi analytical solution (not shown) is different from the numerical complete HDRB behaviour in terms of vertical stress σ_z, due to horizontal displacement. In this respect, the influence of multilayered geometry cannot be neglected, leading to global compression and tension areas (Fig. 8) which are not described by the analytical model.

The Corradi solution has been here extended by introducing a new hypothesis on the shape of the σ_z stresses under horizontal loading. A shape function has been defined on the basis of the general stress behaviour observed on the numerical results, and, in particular, within the area subjected to positive (tension) σ_z stresses. The normal tension stress due to horizontal load has been stated as a function of the value of the parameter *k* (ratio of horizontal displacement to total rubber height), of the height *z* of the layer and on the abscissa *x* (Fig. 4b). The function has a sinusoidal variation in terms of *x*, with a phase depending on *z* and *k* (eq. 2, Fig. 5b):

$$\sigma_z = 1 \cdot k \cdot \sin\left(\frac{\pi x}{R} + \frac{k\pi}{3R}\left(z - \frac{H}{2}\right)\right) \tag{2}$$

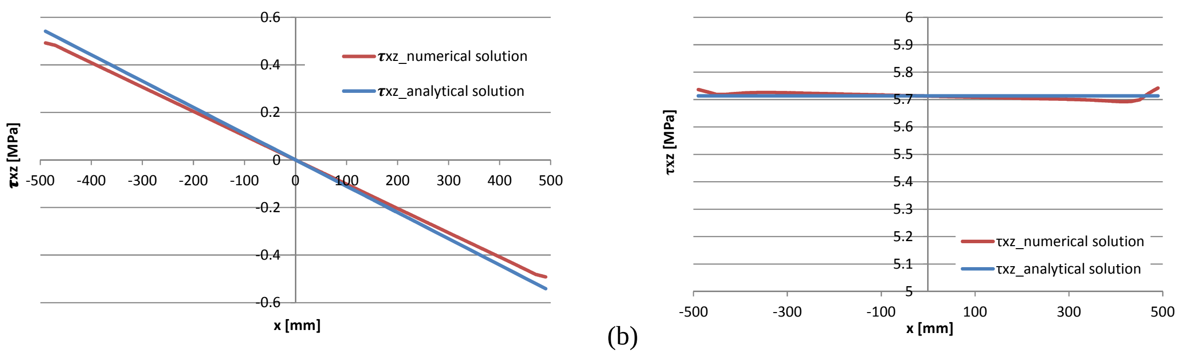
The resultant force calculated on the symmetry vertical plane is always zero under horizontal loading, as the wave length of function in eq. 2 is equal to R.

In terms of global reactions, Fig. 3a shows a good matching between the analytical and numerical solutions, only for horizontal displacement. Concerning local stresses, σ_z due to vertical load (Fig. 5a) and τ_{xz} due to vertical load (Fig. 6a) and horizontal displacement (Fig. 6b) are in good agreement, when numerical FE solution for complete isolator is compared with analytical solution for a single rubber layer. σ_z stresses due to horizontal displacement (Fig. 5b), approximated by shape function in eq. 2, are in good agreement with numerical solution, in particular in traction zones (Fig. 8) for *k*>200%.



(a) (b)

Fig. 5: analytical and numerical σ_z stresses in HDRB: vert. load 10’000 kN (a), *k*=300% horizontal displ. (b)



(a) (b)

Fig. 6: analytical and numerical τ_{xz} stresses in HDRB: vert. load 10’000 kN (a), *k*=300% horizontal displ. (b)

HDRB LIMIT STATE DOMAIN

Rubber compounds may suffer damage and failure for delamination (detachment of rubber layers from steel plates), tensile rupture (rubber ultimate strength under tension), tearing (indefinite propagation of a crack), fatigue (indefinite propagation of a crack, induced by a large number of stress cycles) and cavitation (large or indefinite expansion of small holes due to hydrostatic tension). Delamination damage condition is accounted in present study.

Yen-Caiazzo limit state domain

Failure tests on HDRB showed that delamination initiates on isolator sides (Fig. 1a). Coherently, the numerical and analytical stress fields exhibit the highest values in the same regions on sides (maximum shear and tension stress). The σ/τ limit domain in [12] [13] was adopted for first damage (eq. 3a)

$$\left(\frac{\sigma_{3T}}{S_{3T}}\right)^2+\left(\frac{\tau_{13}}{S_{130}}\right)^2=1 \tag{3a}$$

$$S_{130}=\frac{2Fh}{\pi R^3}=\frac{2*20000*5}{\pi 245^3}=4.33MPa \tag{3b}$$

$$S_{3T}=17.5MPa \tag{3c}$$

where σ_{3T} is the tensile stress orthogonal to rubber plane, S_{3T} is the tensile strength, τ_{13} is the shear stress and S_{130} is the reference shear strength. Strength parameters were determined from data provided by the manufacturer [4]: tensile strength is 17.5 MPa while shear strength was calculated from the vertical load (20’000 kN, 1:2 scale isolator) that caused the first change in vertical stiffness. The analytical solution [11] for vertical load provides corresponding shear stress, at isolator sides (eq. 3b). First damage is assumed to occur when a single point of the isolator reaches the limit state condition. Regions with high compression stresses (Fig. 8) are not considered in this study, since there was no experimental evidence of damages in these regions for actual geometry and loading.

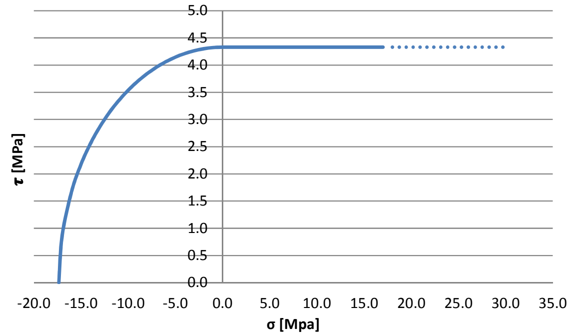


Fig. 7: Yen–Caiazzo first damage domain, for S_{130}=4.33 MPa and S_{3T}=-17.5 MPa (σ>0 compression, in figure)

Numerical and analytical limit state domains

Regions where first damage due to delamination is expected to occur are those where normal stresses are tractions and shear stresses due to vertical load sum to shear stresses due to horizontal displacement, with same sign. Fig. 8 shows locations of these critical points in a HDBR, where Yen-Caiazzo limit state [12][13] is firstly reached.

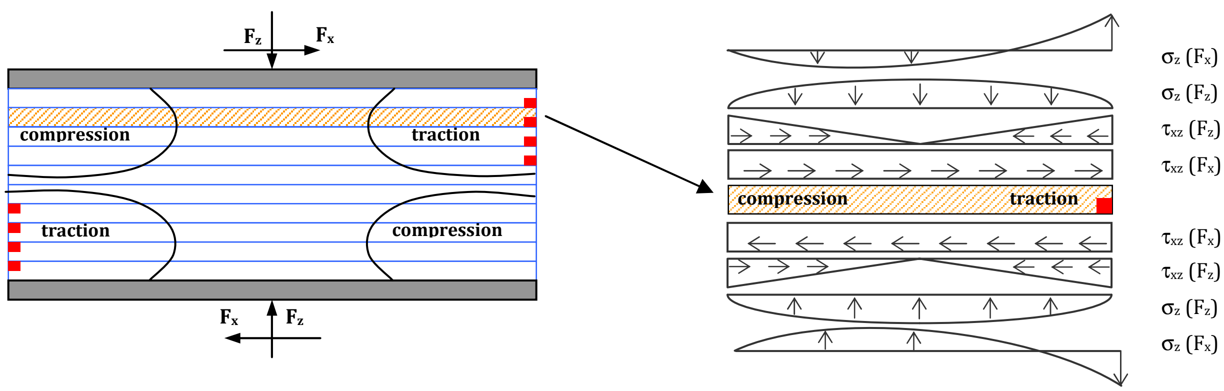


Fig. 8: Critical points in a HDRB and qualitative stress state in a rubber layer located in the isolator top half

The numerical H-V domain (Fig. 10a) was computed imposing a vertical load and determining the corresponding horizontal displacement *k* (Fig. 10b) that causes a single point to reach the first damage condition.

For the analytical domain statement (Fig. 10a), shear and normal stresses due to vertical load and shear stress due to horizontal displacement are retrieved from Corradi analytical solution [11] for a single rubber layer, while for the normal stress due to horizontal displacement $\sigma_{3T} = 1 \cdot k$ is assumed (eq. 2, calculated at HDRB middle height *z*=H/2, at side *x*=R). The procedure in Fig. 9 is applied to calculate the analytical domain in terms of global forces, for a given *k*:

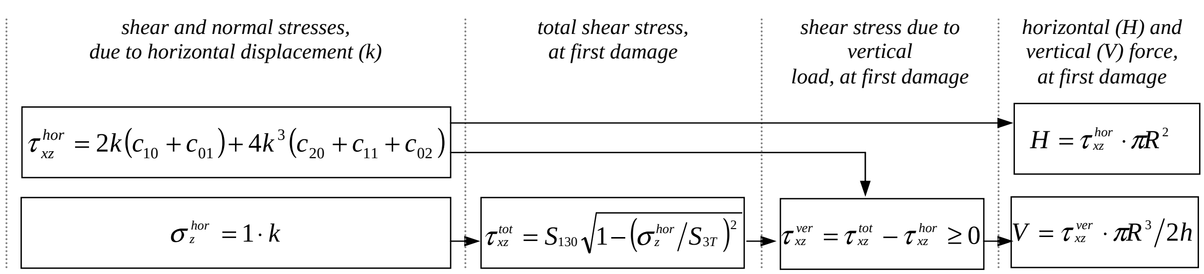
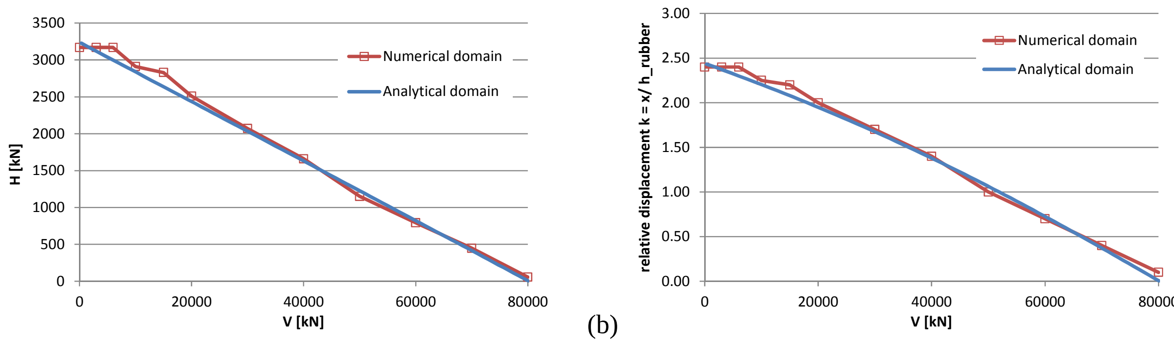
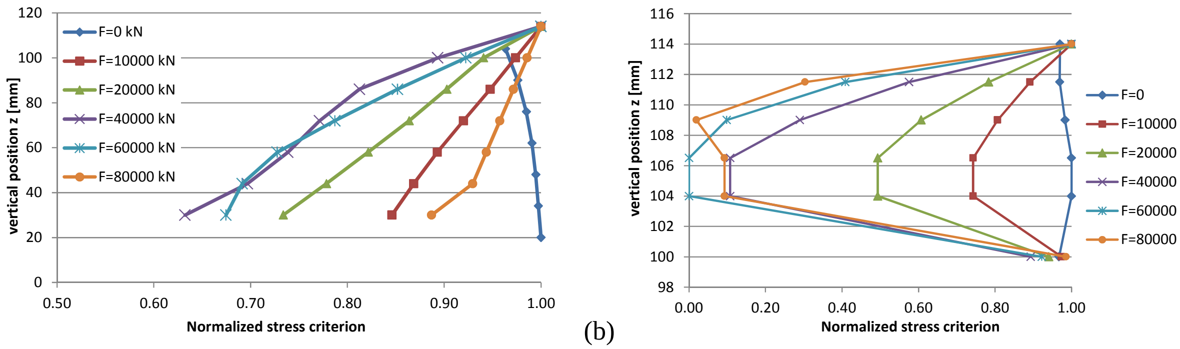


Fig. 9: Procedure for analytical domain calculation, in terms of global forces, for a given *k* horizontal displacement



(a) (b)

Fig. 10: Analytical and numerical first damage domains (full scale) in terms of vertical and horizontal forces (a), and relative horizontal displacement *k* at which first damage condition is reached for a given vertical load (b)



(a) (b)

Fig. 11: Normalized stress criterion, (a) at different location in the isolator (maximum value at each layer), (b) at different location in a single rubber layer, extracted form the isolator

CONCLUSIONS AND FUTURE DEVELOPMENTS

The first part of the work addressed the stress state in the HDRB device. A refined FE model of a single rubber layer was set to perform preliminary evaluation on mesh sensitivity and potential sources of numerical instabilities (see also [5]). It has been shown how the number of FEs adopted in thickness plays a crucial role in tangential stresses due to vertical load, whose magnitude affects the limit state domain significantly. Furthermore, global behaviour of the FE model was compared to experimental results performed at FIP laboratories on 1:2 scale isolator [4]. The comparison showed optimum agreement in terms of horizontal stiffness, while vertical stiffness is highly affected by the exact estimation of rubber compressibility.

Corradi et al. [11] proposed an analytical formulation for stresses in a single rubber layer, subjected to vertical and horizontal loading separately, based on approximate solution in large displacement, for different hyperelastic constitutive laws. The Corradi solution was found to be accurate in predicting all but one stress state also in the HDRB complete device, since rubber layers behave almost as a single individual rubber layers acting in series. The present work extended and applied this solution to the complete isolator, allowing predicting also vertical normal stresses in the isolator, which is significantly different than the Corradi solution for a single rubber layer. The proposed Modified Corradi analytical formulation was compared to numerical solutions and was considered to be accurate in predicting the stress field in the HDRB, subjected to vertical load and horizontal displacement, at least in regions where first damage is more likely to occur.

Extensive numerical tests were performed to verify the possibility to decouple horizontal and vertical actions (see also [5]) . The error due to superimposing the effects of each load condition was found small enough to confirm the validity of the analytical solution for first damage domain assessment.

Rubber compounds may suffer damage and fail for delamination, tensile rupture, tearing, fatigue and cavitation. Delamination damage condition is accounted in present study by a Yen-Caiazzo limit state domain [12][13], tuned against mechanical properties provided by the manufacturer, in terms of rubber tensile strength and maximum tangential stress due to maximum vertical load [3][4]. In the second part of the work, the HDRB first damage domain was addressed by means of both the FE model and analytical solution. The two approaches led to very close bi-dimensional first damage domains, expressed in terms of maximum horizontal load for a given vertical load. The domain represents the combination of forces that generates the very first damage at a single location inside the HDRB, whose bearing capacity and stiffness properties are still unchanged.

The study has been developed for fully incompressible rubber, although significant results were obtained in case of nearly incompressible rubber, which will become a future development for the current research.

The results obtained from the first application of step 1 to 4 of the seismic fragility evaluation procedure presented in Perotti et al. [2], also allows defining which mechanical parameters are necessary to be required from the manufacturer.

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