Hand Calculations of Rubber Bearing Seismic Izolation System for Irregular Buildings in Plane

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Abstract—**Base isolation isn't a new philosophy in civil engineering. Although, only in last decades the seismic base isolation systems are spread around the world. There are several industries producing many types of isolation devices and supplying the civil engineers with the necessaries design data. The designing procedures are mainly going through complicated nonlinear analyses as required from national design codes. The analyses are carried out with advanced computer programs by trained and skilled engineer. For a better understanding or even as a test patch, the designer must use hand calculations of such structures. These analyses are equivalent linear static, but the engineer can consider some important nonlinear parameters of isolation units. When nonlinear properties are met, the calculation goes through iteration cycles. In such a case, if a mistake occurs in one cycle, it can be corrected in the next one. For calculation of seismic forces the response spectrums are used with the equivalent stiffness and dumping of isolations system at a resent displacement. In the analyses will be involved the torsional and overturning moment as well. For the elastomeric isolator, the nonlinear properties will be used and the stability analyses will performed.**

Keywords-isolation system, seismic force, equivalent stiffness, hand calculations

I. Introduction

In this paper will be shown the hand calculation for a seismic isolation system consist of rubber bearing devices. The isolation system supports a six stories mid-rise building with plane asymmetry. The building's loads are carried by a frame structure which is assumed to remain in elastic domain. Drifts in the structure are much smaller than the drift in isolation system. So, for dynamic analyses, a single lump mass model can be taken. Characteristics for the rubber bearings are taken from manufacture schedule result from standard tests.

The isolation system is design according to Eurocode-8 provisions for equivalent linear analysis described in prEN 1998-1:2003. Because the characteristics of the rubber are sensitive to the shear strains, the effective stiffness and dumping are displacement dependent. So, the analyses are following an iterative procedure till the design displacement converges to a reliable stable value. The spectral values must be calculated for effective period of each cycle. The axial force acting in isolator unit must reflect the effect of overturning moment due to seismic force. Simultaneously, the torsional in plane moment must be calculated to determine the maximum isolator's displacements.

The initial vertical loads acting on isolator will be calculated according to the corresponding surface of superstructures that they support. The initial values for effective stiffness and dumping will be taken for shear strain $\gamma=1$. For shear strain bigger than 1, the effective values attempt to stabilize their amplitudes. For $\gamma<1$, the necessary correction of these value must be done according the manufacture schedule.

II. Elastomer Characteristic

The rubber compound for the production of elastomeric isolators used in our study is chosen the MVBR-0468 (X 0.4R) produced by Bridgestone with certification on December 2012.

The effective dynamic shear modulus G_{eff} and the equivalent dumping ζ are function to shear strain. In our case the values for these parameters are given by the producer at shear strain $\gamma=1$ respectively $G_{eff}=0.392$ MPa and $\zeta=22\%$. Both parameters are sensitive to shear strains and their relationships to γ are given from the following expressions. For small values of γ the elastomeric isolator is stiff enough to avoid excessive displacements under low dynamic intensity of external loads such as wind [5].

$$G_{eff}(\gamma) = 0.054\gamma^4 - 0.416\gamma^3 + 1.192\gamma^2 - 1.583\gamma + 1.145 \quad (1)$$

$$\xi_{eff}(\gamma) = - 0.006\gamma^3 + 0.018\gamma^2 - 0.008\gamma + 0.216 \quad (2)$$

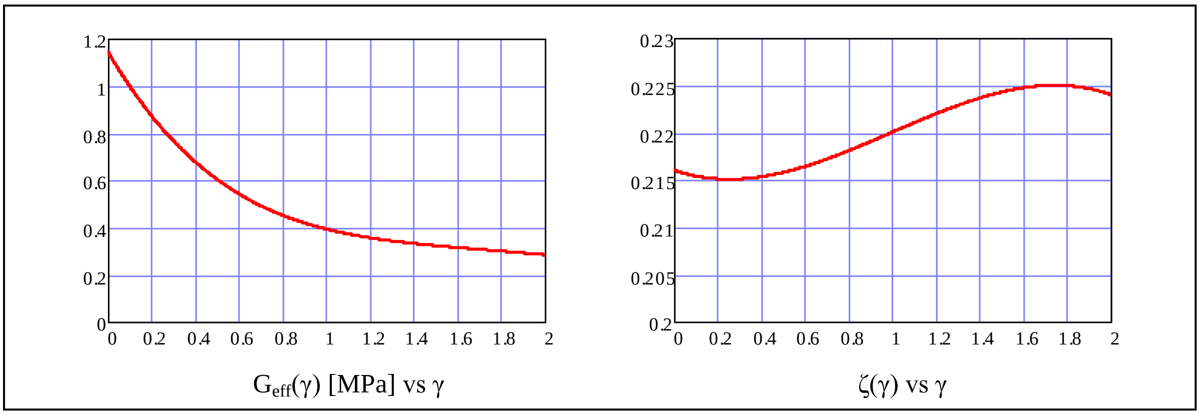

Figure 1. Elastomeric characteristics for high dumping rubber with normal hardness

III. Building Parameters

The building consists of six stories with equal height of 3.3m with plane irregularities as shown in figure 1. The weight for each floor is taken uniformly distributed with intensity of 10kN/m^2. Centre of mass is assumed to be the same with the geometrical centre of the floors. The centre of mass is not a fixed point. In Eurocode-8 is recommended an accidental eccentricity of 5% of building length perpendicular to seismic action. For each column base, the static axial compression force is calculated. With the values of axial loads, in the manufacturer schedule we select the types of rubber bearings.

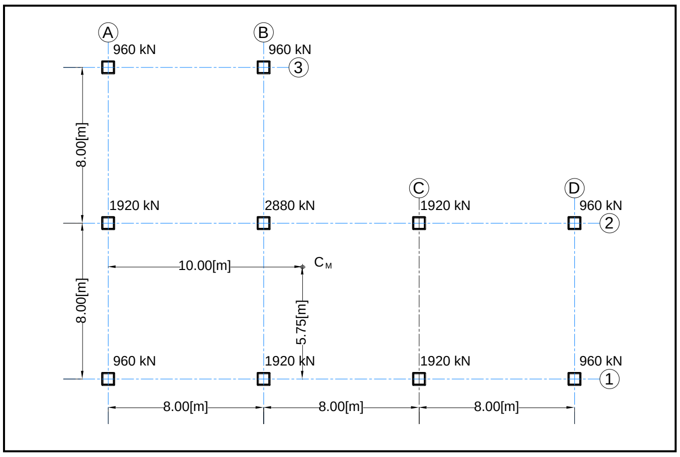

Figure 2. Building plan view

IV. Properties of Isolation System

Firstly we select the rubber bearing isolators depending on vertical static loads and the desire effective period of 2.5 s and target shear strain γ=1.5 . The desired effective stiffness can be derived from the following expression [3]:

$$K_{eff} = 4 * \pi^2 * M / T_{eff}^2 \qquad (3)$$

where "M" denote the seismic mass supported by the isolator unit equal to W/g. "W" is the weight of superstructure and the base for isolating system.

Because the building is rather small, the isolator unit will be taken equal for each support. The elastomeric rubber bearings laminated with steel shims have a very large vertical stiffness. Although, they will be check for different values of axial loads which vary among the columns. Grouping the isolators make them more economical and easy to implement in site. The desired horizontal effective stiffness for the ten isolators as one is:

$K_{eff} = 4 * 3.14^2 * 1566 / 2.5^2 = 9882$ kN/m and for one unit $k_{eff} = K_{eff} /10 = 988.2$ kN/m

The effective stiffness can be calculated using the simplify formula considering only the shear deformation:

$$k_{eff} = G_{eff} * A / t_r \qquad (4)$$

For γ=1.5 we have the effective shear modulus G_{eff} = 0.322 MPa and assuming the total height of the rubber t_r=100mm, the cross-section area of the isolator result:

$$A^{(A)} = k_{eff}^{(A)} * t_r / G_{eff} = 988.2 * 0.1 / 322 = 0.3069\ m^2 \qquad (5)$$

Choosing the diameter D = 0.65m with A = 0.3317m2 and k_{eff} = 1067 kN/m

The effective stiffness of isolation system for horizontal directions is calculated as sum of single devices. In our case the K_{eff} = 10670 kN/m.

The effective period of isolation system is defined from the following expression:

$$T_{eff} = 2 * \pi * \sqrt{(M / K_{eff})} = 2 * 3.14 * \sqrt{(1566 / 10670)} = 2.4s \qquad (6)$$

The effective period of horizontal motion is approximately to the target one and no further adjustment must be done. If there is a difference, we can increase or decrease the total height of the rubber.

V. Calculation of Displacements

The lateral displacement for each isolator unit is compound from linear displacement caused by the horizontal seismic force acting on superstructure and the displacement caused by torsion moment due to eccentricity of seismic force.

First, the spectral acceleration is calculated for the resent period of the system. The spectral acceleration are build according to Eurocode-8 for the behaviour factor q=1 (totally elastic), peak ground acceleration a_g=4m/s^2 and different level of dumping [2].

$$0 \le T \le T_B : S_e(T) = a_g \cdot S \cdot \left[1 + \frac{T}{T_B} \cdot (\eta \cdot 2.5 - 1)\right]$$

$$T_B \le T \le T_C : S_e(T) = a_g \cdot S \cdot \eta \cdot 2.5$$

$$T_C \le T \le T_D : S_e(T) = a_g \cdot S \cdot \eta \cdot 2.5 \left[\frac{T_C}{T}\right]$$

$$T_D \le T \le 4s : S_e(T) = a_g \cdot S \cdot \eta \cdot 2.5 \left[\frac{T_C T_D}{T^2}\right]$$

$$\eta = \sqrt{\frac{10}{5+\xi}} \ge 0.55$$

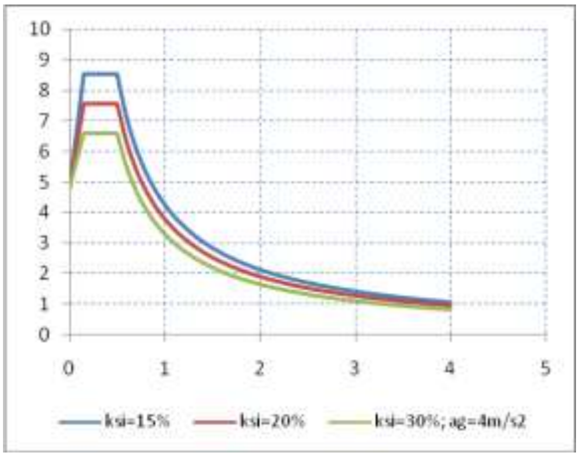

Figure 3. Elastic acceleration spekra according Eurocode-8

Assuming the initial dumping ζ=22.4% and period T_{eff} = 2.4s, in the response spectrum we get the spectral acceleration S(a)=1.26 m/s^2 which yield the seismic force of magnitude:

$$E_1 = M * S(a) = 1566 * 1.26 = 1973\ kN \qquad (7)$$

The displacement for the first step of analyses is equal to

$$\Delta = E_1 / K_{eff} = 1973 / 10670 = 0.185\ m \qquad (8)$$

The effective stiffness used in the above calculation corresponds to displacement of

$$\Delta = t_r * \gamma = 0.10 * 1.5 = 0.15\ m \qquad (9)$$

so its value must be adjusted to the calculated displacement.

The calculated displacement correspond to the shear strain $\gamma = \Delta / t_r$ = 0.185/0.10 = 1.85. The effective values of rubber at this strain are G_{eff} =295 kPa, K_{eff} =9775kN, T_{eff} = 2.51s and ζ=22.5%.

With T_{eff} = 2.51s, in the response spectrum we get S(a)=1.15 m/s^2 and repeating the above calculations we achieve the next displacement Δ=0.184m, which differ less than 5% to the previous displacement.

Because the isolator units are not in symmetrical position and have different properties, the centre of rigidity for isolation system must be calculated using the expressions:

$$X_{C.R} = \Sigma k_{i,eff} * x_i / K_{eff} \quad \text{and} \quad Y_{C.R} = \Sigma k_{i,eff} * y_i / K_{eff} \qquad (10)$$

For the isolation system the coordinates of rigidity centre are $X_{C.R}$ = 10.4m and $Y_{C.R}$ = 6.4m referring to the left-bottom isolator unit. Hence, the eccentricity is calculated taking into account the accidental eccentricity of 5% for both directions:

$$e_x = (X_{C.R} - X_{C.M}) \pm 0.05L \quad \text{and} \quad e_y = (Y_{C.R} - Y_{C.M}) \pm 0.05B \quad (11)$$

In the example will be shown the calculation only for seismic force acting on "Y" direction, so the eccentricity and the torsion moment is calculated

$$e_x = (10.4 - 10.0) + 0.05*24 = 1.6\text{m}.$$

$$M_T = E_1 * e_x = 1801 * 1.6 = 2882 \text{ kNm}. \quad (12)$$

Proceeding the analyses with calculations of torsional stiffness for the isolation system and the horizontal displacement due to rotation in plane of the structure:

$$K_\theta = \Sigma k_{i,eff} * (x_{i,R}^2 + y_{i,R}^2) = 1107312 \text{ kN/rad} \quad (13)$$

$$\theta = M_T / K_\theta = 0.0026 \text{ rad} \quad (14)$$

For the isolator placed under the columns of left axis, the additional and the total displacement in "Y" direction are calculated as

$$\Delta_{\theta,Y} = \theta * x_{i,R} = 0.0026 * 10.4 = 0.027\text{m} \quad (15)$$

$$\Delta_Y = \Delta_{\theta,Y} + \Delta_{\delta,Y} = 0.184 + 0.027 = 0.211\text{m} \quad (16)$$

$$\gamma = \Delta / t_r = 0.211/0.10 = 2.11$$

For the isolator placed under the columns of right axis, the additional and the total displacement in "Y" direction are calculated as

$$\Delta_{\theta,Y} = \theta * x_{i,R} = 0.0026 * 13.6 = 0.035\text{m}$$

$$\Delta_Y = \Delta_{\theta,Y} + \Delta_{\delta,Y} = 0.184 - 0.035 = 0.149\text{m}$$

$$\gamma = \Delta / t_r = 0.149/0.10 = 1.49$$

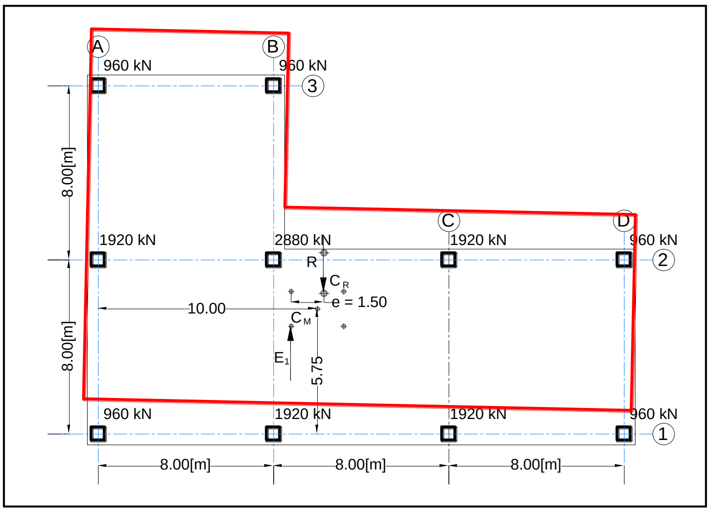

Figure 4. Building displacemet in plan.

The isolator units placed under the columns to the left of the rigidity centre will have displacements greater than the isolators to the right. The effective stiffness is depended to the displacement and must be adjusted to the real shear strain. With the new effective stiffness for isolators units, the new centre of rigidity is recalculated. It's easy to predicted that centre of rigidity will move to the right as the left side of isolation system become more flexible. This will yield in a bigger angle of rotation and higher values of displacements. At the mean time there is an increase in torsional stiffness. Repeating the calculations till the two resent displacements doesn't differ more than 5%. In the table (1) are given the modified effective stiffness for each isolator to the new respective shear strains. This procedure can be done with very simple computer program to avoid possible mistakes.

TABLE I. ISOLATOR EFFECTIVE STIFFNESS AT MAXIMUM DISPLACEMENTS

Axis	***A***	***B***	***C***	***D***	
1	909	965	1015	1071	0
2	909	965	1015	1071	8
3	909	965			16
	0	8	16	24	**Coordinate**

From the Equation (10), the new coordinate for the centre of rigidity and eccentricity are:

$$X_{C.R} = \Sigma k_{i,eff} * x_i / K_{eff} = 10.9m$$

$$Y_{C.R} = \Sigma k_{i,eff} * y_i / K_{eff} = 6.3m$$

$$e_x = (X_{C.R} - X_{C.M}) \pm 0.05L = (10.9 - 10) + 0.05*24 = 2.1m$$

The new additional displacement is calculated as follow:

$$M_T = E_1 * e_x = 1801 * 2.1 = 3782 \text{ kNm}$$

$$K_\theta = \Sigma k_{i,eff} * (x_{i,R}^2 + y_{i,R}^2) = 1113672 \text{ kN/rad}$$

$$\theta = M_T / K_\theta = 0.0034 \text{ rad}$$

For the isolator placed under the columns of left axis, the additional and the total displacement in “Y” direction are calculated as

$$\Delta_{\theta,Y} = \theta * x_{i,R} = 0.0034 * 10.9 = 0.037m$$

$$\Delta_Y = \Delta_{\theta,Y} + \Delta_{\delta,Y} = 0.184 + 0.037 = 0.221m$$

$$\gamma = \Delta / t_r = 0.22/0.10 = 2.2$$

For the isolator placed under the columns of right axis, the additional and the total displacement in “Y” direction are calculated as

$$\Delta_{\theta,Y} = \theta * x_{i,R} = 0.0034 * 13.1 = 0.044m$$

$$\Delta_Y = \Delta_{\theta,Y} + \Delta_{\delta,Y} = 0.184 - 0.044 = 0.14m$$

$$\gamma = \Delta / t_r = 0.14/0.10 = 1.4$$

Proceeding to the next cycle we get the maximum calculated displacement of 0.225m. According to Eurocode-8 the isolator unit must be design for a maximum displacement 1.2 times greater than the calculated displacement.

$$\Delta^{max}_Y = \Delta_Y * \gamma_x = 0.225 + 1.2 = 0.27m$$

$$\gamma = \Delta^{max}_Y / tr = 0.27 / 0.10 = 2.7$$

The shear strain $\gamma = 2.7$ is almost twice than target design strain $\gamma = 1.5$. So, we repeat the analyses assuming the total rubber height 200mm and the isolator diameter D=850mm which yields the following values:

$$K_{eff} = n * G_{eff} * A / t_r = 10 * 322 * 0.567 / 0.2 = 9128.7 \text{kN/m}$$

$$T_{eff} = 2 * \pi * \sqrt{(M / K_{eff})} = 2 * 3.14 * \sqrt{(1566 / 9128.7)} = 2.6s$$

$$E_1 = M * S(a) = 1566 * 1.07 = 1676 \text{ kN.}$$

$$\Delta = E_1 / K_{eff} = 1676 / 9128.7 = 0.183 \text{ m.}$$

$$M_T = E_1 * e_x = 1676 * 2.1 = 3520 \text{ kNm}$$

$$K_\theta = \Sigma k_{i,eff} * (x_{i,R}^2 + y_{i,R}^2) = 1043589 \text{ kN/rad}$$

$$\Delta_Y = \Delta_{\delta,Y} + \Delta_{\theta,Y} = 0.183 + 0.036 = 0.219m$$

$$\Delta^{max}_Y = \Delta_Y * \gamma_x = 0.219 * 1.2 = 0.263m$$

$$\gamma = \Delta^{max}_Y / tr = 0.263 / 0.20 = 1.31$$

VI. CALCULATION FOR VERTICAL LOADS.

The vertical loads acting on a single isolator unit is compound by dead load and live load as statics, and vertical load by overturning moment as dynamic load. The isolator unit must be capable to support the sum of these vertical loads taken from load combination in earthquake situation. Also, the isolation unit must be design to have a high vertical stiffness, which can be achieved by having a desire vertical free vibration period of 0.1 seconds.

For isolation system the target stiffness is as below

$$K_V = 4 * \pi^2 * M / T_v^2 = 4 * 3.14^2 * 1566 / 0.1^2 = 6176053 \text{ kN/m}$$

$$k_{i,V} = K_V / 10 = 617605 \text{ kN/m}$$

The composite module of elasticity can be calculated by the following expressions

$$E_{i,C} = k_{i,V} * t_r / A = 617605 * 0.20 / 0.567 = 217850 \text{ kN/m}^2 \quad (17)$$

From the other side the composite module of elasticity is given as function of isolator factor S = R / 2t where "R" is the radius of isolator cross-section and "t" is the thickness of a single rubber layer.

$$E_{i,C} = 6 * G_{(\gamma=20\%)} * S_1^2 = 6 * G_{(\gamma=20\%)} * D_{(A)}^2 / 16t^2 \quad (18)$$

$$t = [(6 * 873 * 0.85^2) / (16 * 217850)]^{1/2} = 0.033\text{m} = 33\text{mm}$$

Assuming seven layers of 28.6mm rubber, six steel shims of 4mm and two endplates. The composite modulus of elasticity more precisely is given by [1]:

$$E_{i,C} = (6 * G * S_1^2 * E_\infty) / (6 * G * S_1^2 + E_\infty) \quad (19)$$

With shape S=7.43 and bulk modulus E_∞ = 1300 MPa the composite modulus for the isolation system is:

$$E_{i,C} = (6 * 873 * 7.43^2 * 1300) / (6 * 873 * 7.43^2 + 1300) = 236551 \text{ kN/m}^2$$

$$K_V = 10 * k_{i,V} = 10 * 236551 * 0.567 / 0.2 = 6706221 \text{ kN/m}$$

$$T_V = 2 * \pi * \sqrt{(M / K_{eff})} = 2 * 3.14 * \sqrt{(1566 / 6706221)} = 0.096 \text{ s}$$

Calculating the axial loads acting upon the isolator units for earthquake load combination. The axial load will be the sum of vertical statics loads and the dynamic load from overturning moment. The overturning moment will be calculated by multiply the earthquake force with the half height of the superstructure along O-X axis. The axial load will be calculated for the isolator with γ_{max} (isolator at axis A_3) and with maximum vertical static load (isolator at axis B_2). The axial loads induced by overturning moment will be calculated assuming the superstructure as rigid body.

$$M_{OX} = E_1 * H_S / 2 = 1676 * 19.8 / 2 = 16592.4 \text{ kN/m} \quad (20)$$

$$N_{sd,i,E} = N_{sd,i} + (M_{OX} / K_\phi) * k_{i,v} * y_i \quad (21)$$

$$N_{sd,E}^{(A\_3)} = 960 + (16592.4 / 221000000) * 617605 * 9.6 = 960 + 445 = 1405 \text{ kN}$$

$$N_{sd,E}^{(B\_2)} = 2880 + (16592.4 / 221000000) * 617605 * 1.6 = 2880 + 74 = 2954 \text{ kN}$$

Because we are using one type of isolator, further on the strength and stability of the central isolator will be check. The critical stress at "zero" strain for the rubber material used is given by the expression [5]:

$$\sigma_{cr} = \alpha_c * \pi/4 * (G_{eq} * E_b)^{0.5} * S_2 \quad (22)$$

$$E_b = E_{cr} (1 + 2/3 * \kappa * S_1^2) / \{1 + E_{cr} (1 + 2/3 * \kappa * S_1^2) / E_\infty\} \quad (23)$$

$$\alpha_c = 0.88 (1-0.07(5 - S_2)) \text{ for } S_2 < 5 \text{ or } \alpha_c = 0.88 \text{ otherwise}$$

$$S_2 = D / t_r \qquad E_{cr} = 3 * G_{eq,(\gamma=1)} \quad \kappa = 0.223$$

$$\sigma_{cr} = 0.8345 * 3.14/4 * (1145 * 10740)^{0.5} * 4.246 = 9758 \text{ kN/m}^2$$

$$\sigma_{cr}'(\gamma) = \sigma_{cr} * (1 - \gamma / S_2) \quad (24)$$

$$\sigma_{cr}'(1.15) = 9758 * (1 - 1.15 / 4.246) = 7115 \text{ kN/m}^2 = 71 \text{ daN/ cm}^2$$

$$\sigma_{sd} = N_{sd,E} / A = 2954 / 0.567 = 5210 \text{ kN/m}^2 = 52 \text{ daN/ cm}^2$$

The horizontal stiffness that we calculate previously doesn't count the presence of vertical load. In the presence of vertical load the horizontal stiffness is modified as below [1]:

$$K_H = K_H^0 [1- (\sigma_{sd} / \sigma_{cr}')^2] = K_H^0 [1- (52 / 71)^2] = 0.46 K_H^0 \quad (25)$$

To avoid the reduction of horizontal stiffness, a very high value for critical stress must achieved by decreasing the thickness of single rubber layers. Choosing the isolator HH085X4R of HH-Series with thickness of one rubber layer 5.7mm the critical stress at maximum strain and stiffness reduction are:

$$\sigma_{cr}'(1.15) = 42000 * (1 - 1.15 / 4.246) = 30625 \text{ kN/m}^2 = 306 \text{ daN/ cm}^2$$

$$K_H = K_H^0 [1- (52 / 306)^2] = 0.97 K_H^0$$

With the above selected isolator, for the design strain, horizontal effective stiffness is insensitive to design axial load value.

The actual first shape factor is $S_1 = D / 4t = 850 / (4 * 5.7) = 37$, which yield a vertical stiffness and the period of vertical free vibration equal to [3]:

$$K_V = 10 * k_V = 10 * EC * A / t_r = 3420 * 10^4 \text{ kN:m}$$

$$T_V = 2 * \pi * \sqrt{(M / K_{eff})} = 2 * 3.14 * \sqrt{(1566 / 34200000)} = 0.042 \text{ s}$$

VII. Check of the Dumping Factor.

The dumping factor ξ is given as ratio of dissipated energy with the critical dumping of the structure. Both values are calculated for the maximum displacement of the isolation system. The dissipation of energy is done in hysteretic manner and equal to the surface of one loop. The hysteretic loop parameters are given by the following parameters as shown in figure 5:

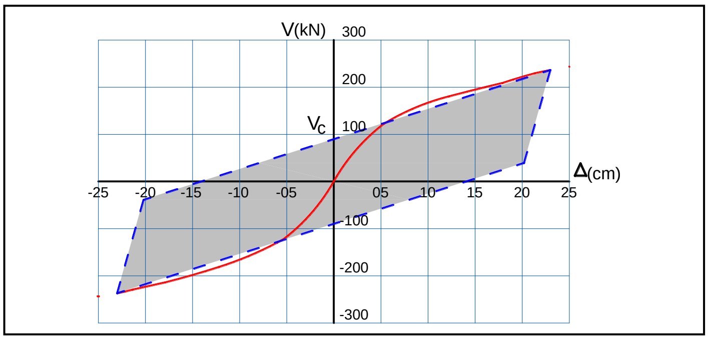

Figure 5. Hysterezis loop at maximum displacement..

$$V = K_{eff} * \Delta, \qquad Vc = * V, \qquad \Delta = t_r * \gamma$$

$$u(\gamma) = -0.0110 * \gamma^3 + 0.0325 * \gamma^2 - 0.0132 * \gamma + 0.3617$$

$$k_2 = K_{eff} * [1 - u(\gamma)] \qquad k_1 = 10 * k^2$$

At shear strain g = 1.15 the hysteretic parameters are as below:

$$u(1.15) = -0.0110 * 1.15^3 + 0.0325 * 1.15^2 - 0.0132 * 1.15 + 0.3617 = 0.373$$

$$\Delta = 0.2 * 1.15 = 0.23 \text{ m}$$

$$V = 1029 * 0.23 = 237 \text{ kN}$$

$$Vc = .373 * 237 = 88 \text{ kN}$$

The area of hysteretic loop, which present the dissipated energy is:

$$\Delta W = 4 * Vc * [\Delta_{max} - Vc / (2 * k_1)]$$

$$\Delta W = 4 * 88 * [0.23 - Vc / (2 * 7020)] = 78.75 \text{ kJ}$$

$$W = 2 * \pi * K_{eff} * \Delta^2 = 2 * 3.14 * 1029 * 0.23^2 = 341 \text{ kJ}$$

$$\xi = \Delta W / W = 78.75 / 341 = 23\%$$

$$\xi_{eff} = -0.006 * 1.15^3 + 0.018 * 1.15^2 - 0.008 * 1.15 + 0.216 = 0.22$$

As we can see the effective dumping is almost the same to the damping calculated from the hysteresis loop and no further adjustments of elastic spectra have to be done. Since the external load and resistant load are accurate, these conclude the design of isolation system.

VIII. CONCLUSIONS.

The hand calculations are a strong tool in understanding the mechanics of the structures. During the analyses the operator must distinguish the parameters that have variable mechanical values and their dependency. The desired target values for crucial parameters must be achieved and are of very important. To reduce the iteration cycles, the initial values must be choose based on strong engineering judgment. This skill is gained through experience and continuing study. The accuracy of calculation depends upon the accuracy of mathematical model used for isolation unit. Fitting the experimental data with polynomial series has shown a very good accuracy and easy to be used. When designing a laminated rubber isolator the dependency of horizontal stiffness from critical stress at different shear strain γ is the main relation and must be evaluate carefully. From the other side, the axial loads yield from overturning moment can't be neglected. The additional axial stresses caused by overturning moment are comparable with theme caused by static loads. This effect influence more the external isolators placed in perimeter. The dependency of horizontal stiffness is associated to both shape factors, especially from the first one and the shear strains. With the increasing of first shape factor, the critical forces increase rapidly and the horizontal stiffness reduction can be neglected. This is attributed to exponential increase of composite modulus of elasticity which makes the isolator behaviour to be ruled only by the shear strain.

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