

Structural instability mechanisms on bridges neoprene bearings

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ABSTRACT

Bearings are subjected to several structural instability mechanisms due to their loads. Several mechanisms

involving buckling are to be analyzed in this article, like strain limit, sliding limit, tensile in steel sheet, rotation limit verification, curvature instability and friction instability to different kinds of loads. Finite Element Method and Symbolic Algebraic Computation were employed in order to analyze behavior in several bearings sections in compliance with European Codes.

Keywords: Bridges dimensions, Elastomeric Bearings, Supports, Neoprene, Sizing, Finite Element Method, Symbolic Algebraic Computation

1 INTRODUCTION

A reinforced elastomer bearing is a vulcanized block of elastomer reinforced internally by steel sheets chemically bonded by the vulcanization process (Machetti, 2007). The elastomer is a macromolecular material that fits in its initial shape and dimensions, after achieving significant strain under the effect of a compression variation.

According to DNIT 091 (2006) reinforced elastomer bearings are the ones that can best combine the necessary properties in a project. Having rubber as its main material, these bearings have the capacity of rotating with low resistance and transmitting the reaction in a well defined area.

The reinforced elastomers are currently the most used in special works of art made of reinforced and prestressed concrete, among many reasons, this is due to the fact that they have not only the low cost but also a great ease of assembly and maintenance. Such bearings have the advantage of allowing translations in all directions besides being highly durable, with excellent resistance to corrosion and vibrations, provide dynamic damping effects and have high compressive strength

The present work will analyze the behavior of certain sections of bearings in reinforced neoprene, for a given combination of loads within a characteristic range of usual loads of medium-sized bridges and viaducts. As a reference, the verifications established by the European Code will be used as well as some

analyses made by a finite element method (FEM) in order to show the workability ranges of such bearings that are used in large scale on several highways, in accordance with relevant standards.

2 ELASTOMER CHARACTERISTIC

The rubber of which the elastomer is made has basically the following properties: modulus of longitudinal elasticity of approximately 2.7MPa, Poisson coefficient of 0.488 which provides a modulus of transverse elasticity of approximately 0.9MPa and has a compressive strength of 12MPa . Because it is a very flexible material, the reinforcing was created to improve the resistance to rigidity of these bearings.

After reinforcing the tendency of the rubber to flow laterally is prevented by the steel, which is drawn, compressing the elastomer, (Vivan, 2015). Fret sheets which are coated with polytetrafluoroethylene (PTFE) decrease transverse strains, and then their stiffness is increased and the compressive strength reaches a value of up to 80 MPa.

The main physical parameter of the elastomer used within the design of the bearing is its transverse shear modulus G . Unless otherwise specified, the nominal value of the transverse shear modulus G is 0.9 MPa.

Under dynamic effects, it is advisable to increase the calculation value of the G modulus of the elastomer. Under the horizontal effect of the exploration loads, a G -module equal to 1.8 MPa is proposed.

There is a G module for low temperatures. At temperatures below -25°C the neoprene begins to crystallize. Some cold countries integrate module G at low temperatures in their design, where there are regions with temperatures below -30°C .

3 METAL LAYERS CHARACTERISTICS

The thickness of the layers must be greater than or equal to 2 mm. The steel used must have the equivalent breaking elongation. The yield strength of the steel to be used within the calculation is therefore 235 MPa, its modulus of elasticity approximately 200,000MPa and Poisson's coefficient equal to 0.3.

The steel sheet must be used to stiffen the bearing in the vertical direction and at the same time so that there is no change in the horizontal displacement or rotation capacity, thus making it a nearly incompressible element. (Leonhardt, 1979).

According to ISO 683, (2004), stainless steel can also be used for bearings, being a forged part of stainless steel X4 CrNiMo 16-5-1 (material No. 1.4418), for a Project of low corrosion in areas of high pressure contact.

4 SIZE VERIFICATIONS

4.1 NORMAL COMPRESSIVE STRESS

The elastomeric cushion should be considered to be an elastic sheet compressed by two rigid elements that have flat surfaces that remain flat after force application.

In the centered compression it is observed that there is a difference in the distribution of the normal stresses in the neoprene. For example, the stresses are higher in the center than in the peripheries of the bearing, because the central region behaves in a confined way, unlike the peripheral regions, which have a greater tendency to expel, have their stress decreased with values that tend to zero as shown in the schematic of Figure 1.

The capacities of the elastomers are limited and the sizing procedure is simple. The primary design limit is the compression effort. It has limited compressive load capacity because the bulging is constrained only by friction at the loading interface and local slip will result in a higher elastomer stress. As a result, the average total compression effort should be given by equation 1.

$$\sigma_N = \frac{V_{\max}}{A} \quad (1)$$

at where:

V_{\max} = maximum vertical load;
 A = surface area of the bearing; and
 σ_N = Normal stress.

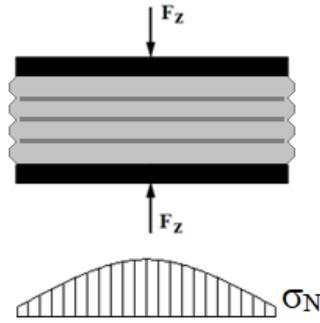
And should be limited by equation 2:

$$\sigma_{N,\lim} = 1,875 \cdot G \left(\frac{a \ b}{2 \ h_{\max}(a+b)} \right) \left\{ 1 - 0,20 \left[\frac{Q_{\max}}{n} \left(\frac{B}{t_i} \right)^2 \right] \right\} \quad (2)$$

at where:

a = smaller size of the bearing;
 b = larger size of the bearing;
 h_{\max} = maximum height of the bearing;
 Q_{\max} = maximum rotation in service on any axis;
 n = number of spacing between the metal sheets;
 t_i = spacing between the metal sheets;
 B = dimension of the horizontal plane normal to the axis of rotation of the bearing;
 G = transversal modulus of elasticity; and
 $\sigma_{N,\lim}$ = Maximum permissible normal stress.

Fig. 1. Distribution of normal stress in a bearing subjected to vertical loading



4.2 LIMITATION OF DISTORTION

The distortion in a reinforced neoprene bearing given by the sum of three factors:

- 1) ε_c = Distortion due to vertical stress, which is given by equation 3

$$\varepsilon_c = \frac{1,5 V_{\max}}{G \left(1 - \frac{V_x}{a'} - \frac{V_y}{b'}\right) \frac{a'^2 b'^2}{2 h_{\max}(a'+b')}} \quad (3)$$

at where:

V_{\max} = maximum vertical load;
 G = cross modulus of elasticity;
 a' = smaller dimension of the steel sheet;
 b' = larger dimension of the steel sheet;
 V_x = horizontal deformation in the x-axis direction;
 V_y = horizontal deformation in the y-axis direction; and
 h_{\max} = maximum height of bearing.

- 2) ε_q = Distortion due to horizontal displacements, which is given by equation 4

$$\varepsilon_q = \frac{F_x}{G a b} \quad (4)$$

at where:

F_x = resulting from the maximum horizontal relative displacement of the parts of the bearing;
 a = smaller size of bearing;
 b = larger size of the bearing; and
 G = transverse modulus of elasticity.

- 3) ε_α = Distortion due to the rotations of the tray, which is given by equation 5

$$\varepsilon_\alpha = \frac{\left(a'^2 \alpha_a + b'^2 \alpha_b\right) t_i}{2 \sum t_i^3} \quad (5)$$

at where:

a' = smaller dimension of the steel sheet;

b' = larger dimension of the steel sheet;

α_a = rotation of the axis parallel to side a of the bearing;

α_b = rotation of the axis parallel to side b of the bearing; and

t_i = spacing between the metal sheets.

And the total distortion ε_t at all points of the bearing for road structures is limited to the ultimate limit state by equation 6:

$$\varepsilon_t = (\varepsilon_c + \varepsilon_q + \varepsilon_\alpha) < 7 \quad (6)$$

The distortions are limited under the effects of forces or horizontal displacements because the ratio must be less than or equal to 1.

The prescriptions relate the efforts and the displacements of short and long duration. On the other hand, the cases of loading to be considered a component of the forces and the concomitant displacements in the two perpendicular directions are in agreement with the vector composition for these verifications.

Note that there are no limitations for ε_c or F_z with the exception of those related to buckling.

4.3 DRIFT IN LAYERS

The layers must be at least 2 mm thick. The standard also requires checking the minimum thickness of the metal layers in the ultimate limit state (ULS). For cell-free (non-perforated) holders, the sheets are of constant thickness t_i . The minimum thickness t_s of the layers is defined by:

$$t_s = \gamma_m \frac{2,6 F_z t_i}{a'b' \left(1 - \frac{V_x}{a'} - \frac{V_y}{b'} \right) f_y} \quad (7)$$

at where:

F_z = maximum applied vertical load;

f_y = elastic limit of the steel that make up the layers;

t_i = spacing between the metal sheets;

γ_m = partial safety factor whose value is 1 within the norm NF EN 1337-2, (2006);

V_x = horizontal deformation in the x-axis direction;

V_y = horizontal deformation in the y-axis direction.

In the case of heavily-requested bearings with rotation close to the buckling limit it is advisable that the ratio between b' and a' is less than 1.24 and that there is an increase in the thickness t of the metal sheets, from 5 to 10%.

4.4 ROTATION LIMITS CONDITIONS

The rotational stability of the bearing in the ultimate limit state shall be verified by equation 8:

$$V_z \geq \frac{(a' \alpha_a + b' \alpha_b)}{K_r} \quad (8)$$

at where:

α_a and α_b = rotations of the axes perpendicular to sides a and b of the bearing;

K_r = factor of rotation that must be equal to 3;

V_z = total vertical deformation.

and the total vertical deformation of V_z by the equation 9 is:

$$V_z = \sum \frac{F_z t_i}{a' b'} \left(\frac{1}{5G \left(\frac{a' b'}{2 h_{\max}(a'+b')} \right)^2} + \frac{1}{E_b} \right) \quad (9)$$

at where:

E_b = elastomer longitudinal modulus of elasticity;

G = elastomer transversal modulus of elasticity;

a' = smaller dimension of the steel sheet;

b' = larger dimension of the steel sheet;

F_z = maximum applied vertical load; and

t_i = spacing between the metal sheets.

It is observed that rotations α_a and α_b must include installation defects. These depend very much on the attention given to the launch, on the precision of the deformation calculations, which depend on the placement and degree of internal homogeneity of the bearing. As far as possible, a method of laying plans will be sought by combining the surfaces, for example with a layer of mortar, and a concrete cream of the tray concreted in loco.

NF EN 1337-3, (2006) proposes the following default values: a) 0.003 radians in the case of methods of placing mentioned conjugate materials; b) 0.010 radians for structures placed directly on the bearing. This setting defect will be adjusted for large rotations α_a or α_b .

4.5 STABILITY TO BUCKLING

The stability to buckling must be verified in the ELU under the conditions pertinent to NF EN 1337-3, (2006).

$$\frac{F_z}{a' b' \left(1 - \frac{V_x}{a'} - \frac{V_y}{b'} \right)} < \frac{2 G a' \left(\frac{a' b'}{2 h_{\max}(a'+b')} \right)}{3 [h_{\max} - t_s (n + 1)]} \quad (10)$$

at where:

a'= smaller dimension of the steel sheet;

b'= larger dimension of the steel sheet;

V_x = horizontal deformation in the x-axis direction;

V_y = horizontal deformation in the y-axis direction;

G = elastic modulus of elasticity of the elastomer;

h_{max} = maximum height of the bearing;

F_z = maximum applied vertical load;

t_s = thickness of the metal sheets; and

n = number of spacing between the metal sheets.

4.6 NON-SLIP CONDITIONS

UNION INTERNATIONALE DES CHEMINS DE FER (UIC) (2006) has a regulation for reinforced elastomers, where slow application loads (permanent loads, thermal effects, retraction) and fast application loads (mobile load, braking, etc.) are separated.

The non-slip check is considered in the absence of anti-chemical bearings.

$$F_{xy} \leq \mu_e F_{z, Gmin} \quad (11)$$

And

$$\frac{F_{z, Gmin}}{a' b' \left(1 - \frac{V_x}{a'} - \frac{V_y}{b'}\right)} \geq 3 \text{ MPa} \quad (12)$$

at where:

F_{z, Gmin} = vertical design force;

F_{xy} = vertical and resulting reaction of the horizontal forces;

μ_e = coefficient of friction between the bearing and the structure;

a'= smaller dimension of the steel sheet;

b'= larger dimension of the steel sheet;

V_x = horizontal deformation in the x-axis direction;

V_y = horizontal deformation in the y-axis direction.

In the calculation of F_{xy} to compose vectorially the horizontal forces coming from all the concomitant actions resulting from combinations of actions, F_{xy} is composed of permanent or variable forces applied directly on the board (wind and braking effect) and permanent or variable efforts due to deformation or distortion (temperature, retraction, volubility, bearing unevenness).

The coefficient of μ_e is imposed by the norm in most cases as:

$$\mu_e = 0,1 + \frac{1,5K_f}{\sigma_m} \quad (13)$$

being:

$$\sigma_m = \frac{F_z}{A' \left(1 - \frac{V_x}{a'} - \frac{V_y}{b'}\right)} \text{ MPa} \quad (14)$$

at where:

$K_f = 0.60$ for the concrete;

$K_f = 0.20$ for other surfaces including mortars and resins;

σ_m = average compression stress of $F_{z,Gmin}$

V_x = horizontal deformation in the x-axis direction;

V_y = horizontal deformation in the y-axis direction.

5 PRESENTATION AND DISCUSSION OF RESULTS

Their behavior was investigated through a moving load variation of 480kN to 3280kN with increments of 200kN, in addition to a permanent load of 920kN at 4700kN with increments of 270kN, and a lateral load of 5kN to 145kN with increments of 10kN, all with 14 breaks.

Moreover, the bearing has a height of 84cm with 7 layers of steel sheet 4mm, 8.5mm and spaced apart by at least 2.5mm coatings.

Calculations were made using symbolic algebraic computation and some comparisons of results using finite element shaped bearings for rupture load compression shown in Figure 2. Such bearings were modeled as solid elements (neoprene) as a isotropic material, with longitudinal modulus of elasticity $E = 2,7\text{MPa}$, transverse elastic modulus $G = 0,9\text{MPa}$. The steel sheets were modeled as area elements as an isotropic material with longitudinal modulus of elasticity $E = 200000\text{MPa}$ and yield stress of 235MPa . In addition, steel sheets with excessive stiffness were molded on the upper and lower faces of the bearing so that the centered point load was applied to the upper sheet. For the area elements 400 finite elements were used for each metal sheet and for the elements of solid 3200 finite elements.

Then the behavior for reinforced elastomeric bearings for several sections were investigated, as follows:

- Section 1 - (400mmx5mm);
- Section 2 - (400mmx600mm);
- Section 3 - (450mmx600mm); and
- Section 4 - (475mmx725mm).

5.1 MAXIMUM COMPRESSIVE STRESS IN A CHARCOAL ELASTOMER

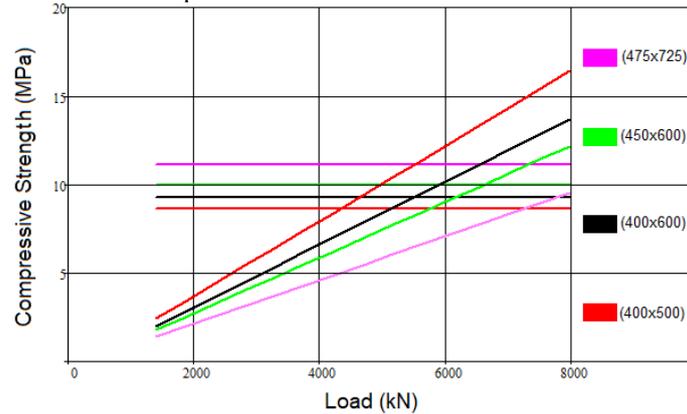
It can be seen in Figure 2 that the maximum compressive stress limit was not met in most cases, for loads considered high within the range.

For the bearing (400mmx500mm) loads higher than 4220kN lead to rupture, whereas for bearings (400mmx600mm) the bursting loads are higher than 4690kN.

Loads exceeding 6100kN lead bearings with a transversal section (450mmx600mm) to rupture. The only section that presented values below the maximum limit for the investigated interval was that of (475mmx725mm). A projection using the trend line of the curve shows that the rupture will occur only for a load of 9747.2kN.

This shows that the larger the cross section, the better it will meet this criterion.

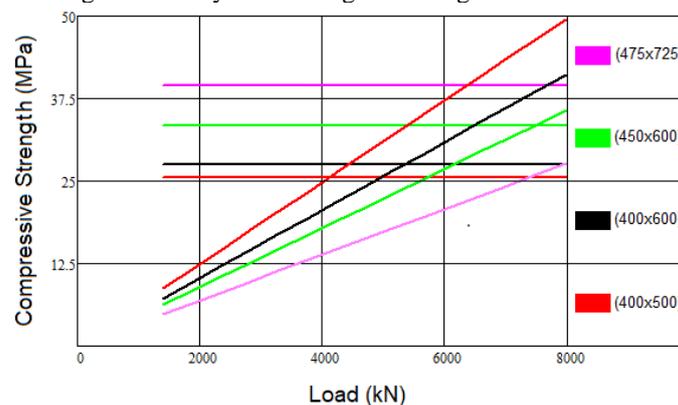
Fig. 2. Maximum compressive stresses in an elastomeric reinforced bearing



5.2 STABILITY TO BUCKLING IN AN ELASTOMERIC BEARING REINFORCED

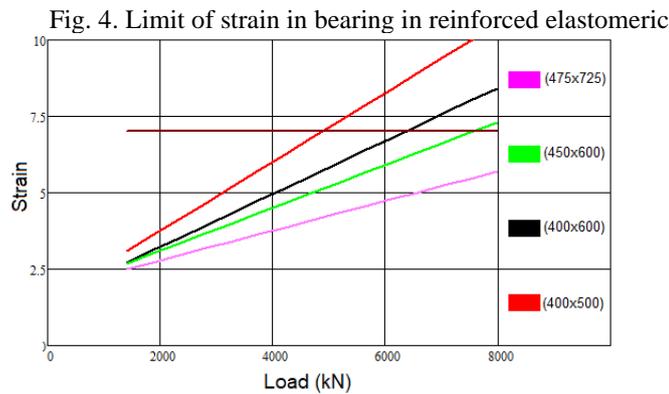
The buckling stability condition behaves very much like the maximum compression stress. For both analyzes the limits were not observed in most cases for loads considered high. For the bearing (400mmx500mm) loads higher than 3750kN lead to instability, while for bearings (400mmx600mm) such fact occurs with loads of 5160kN. The load of 7040kN instabilizes the bearing with a transversal section of (450mmx600mm). The only section that presented values below the maximum limit for the investigated interval was that of (475mmx725mm). A projection using the trend line of the curve shows that for a load of 11387.5kN the limit will not be met, which shows that the larger the transversal section, the better it will meet this verification.

Fig. 3. Stability of buckling in bearing in reinforced elastomeric



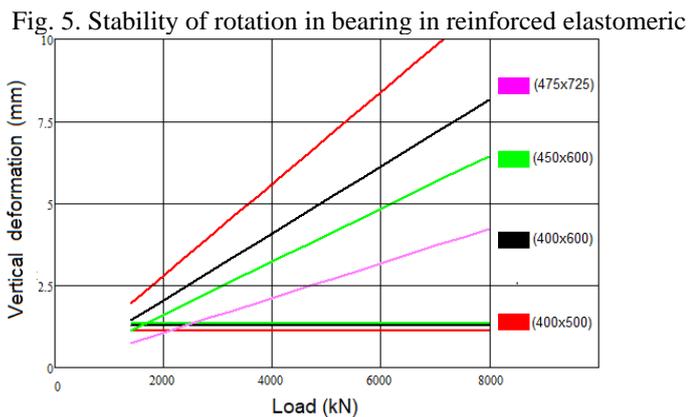
5.3 LIMIT OF STRAIN IN BEARING IN REINFORCED ELASTOMERIC

The strain limit has a condition where no bearing can exceed the maximum specific strain of value equal to 7. It is clear that the smaller the transversal section area, the more susceptible it will be to strain more than the one permitted by NF EN 1337-3, (2006). For the bearing (400mmx500mm) loads above 5160kN lead to this limit of strain, while for bearing (400mmx600mm) this fact occurs for loads of 6570kN, and the load of 7890kN instabilizes the bearing with a cross section of (450mmx600mm). The only section that presented values below the maximum limit for the investigated interval was that of (475mmx725mm). A projection using the trend line of the curve shows that only for a load of 10687.5kN the upper limit of use of this bearing will not be met.



5.4 STABILITY TO ROTATION IN BEARING IN REINFORCED ELASTOMERIC

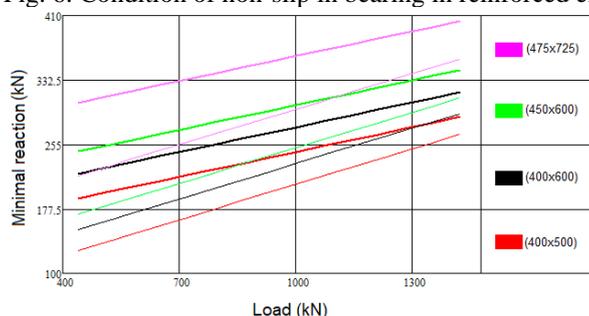
When instability is investigated, it becomes increasingly critical with low value loads, and the greater the transversal section, the less unstable this criterion will be. Transversal section (400mmx500mm) and (400mmx600mm) transversal sectional bearings comply with the specification of NF EN 1337-3, (2006) for the entire range analyzed. The transversal section bearing (450mmx600mm) was unstable only for loads of less than 1400kN, while that of transversal section (475mmx725mm) was unstable for loads below 2810kN. By analyzing the function of the trend line of the bearing given by the two upper functions of the graph, it is calculated that, for the first, the instability would occur with a negative load, that is, from the bottom up, and, for the second, with a loading of approximately 1000 kN.



5.5 FIRST CRITERION FOR CONDITION OF NON-SLIP IN BEARING IN REINFORCED ELASTOMERIC

The sliding condition takes into account the minimum load. For the entire verification curve there is a limit curve. For the interval investigated all sections met the standard NF EN 1337-3, (2006). As shown in the graph of Figure 6, larger sections have higher frictional forces. Analyzing the meeting of the trend lines of each pair, the bearing of (475mmx725mm) has the condition that the minimum load of 2486,1kN is not met. For the section of (450mmx600mm) a load of 2129,1kN is also not met. For the (400mmx600mm) section a load of 2019,2kN is also not met, and for the smaller section of (400mmx500mm) a load of 1905,1kN is also not met. Note that the smaller the section, the more susceptible they are of not meeting the non-slip condition when the loads increase.

Fig. 6. Condition of non-slip in bearing in reinforced elastomeric

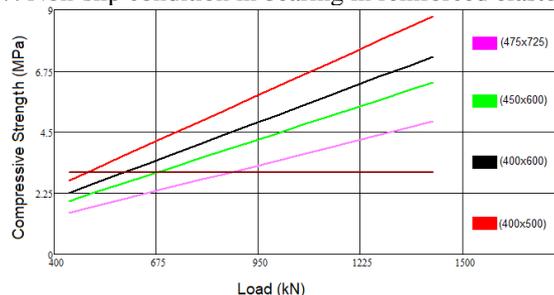


5.6 SECOND CRITERION FOR CONDITION OF NON-SLIP IN BEARING IN REINFORCED ELASTOMERIC

The second non-slip condition criterion takes into account lower limits. It is observed from the graph of Figure 7 that, the smaller the cross section, the more likely to meet the criterion proposed by NF EN 1337-3, (2006) it is, however, for the interval investigated all sections presented unstable zones. The section bearing (400mmx500mm) is the most stable of all, and only does not meet the condition for values less than 510kN. The section bearing (400mmx600mm) must have load values greater than 650kN to meet such specification.

The bearings with larger sections (450mmx600mm) and (475mmx725mm), respectively, should have minimum loads greater than 720kN and 930kN, to meet the second criterion of non-slip condition.

Fig. 7. Non-slip condition in bearing in reinforced elastomeric

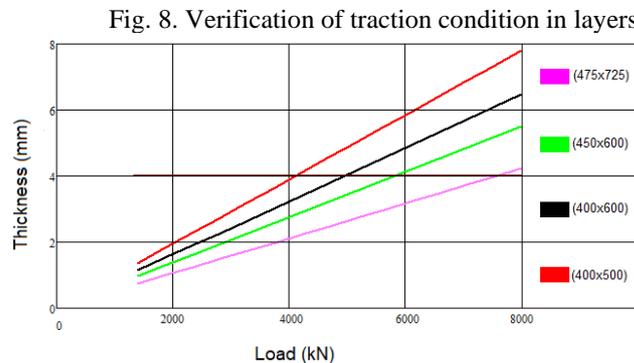


5.7 VERIFICATION OF THE TRACTION CONDITION IN THE LAYERS

For the model adopted, a steel sheet with a thickness of 4mm was used. The thickness of the layers must be sufficient to withstand the traction to which they are subjected. The graph of Figure 8 shows that in the model adopted this verification is not met for the steel used with lower load values and with smaller bearings.

If we compare with the compressive stability of the elastomer, the values of limiting loads are practically the same for the two smaller bearings investigated and smaller for the larger ones for the traction check.

This difference is shown in 7.7% for the bearing with dimensions (450mmx600mm), since the limiting load ranged from 5630kN to 6100kN and 22.95% for the largest bearing (475mmx725mm) that had its load ranging from 7510kN to 9747.2kN.



5.8 CHECKING THE BEHAVIOR OF THE COMPRESSION AND DISPLACEMENT STRESS USING MEF

Figures 9, 10, 11 and 12 show the compression stresses and the maximum vertical displacement, in the largest lateral transversal section of the investigated, for their respective rupture loads.

As seen in the graph of Figure 2, the transversal section bearing (400mmx500mm) reached its compression limit for a load of 4220kN.

For this load it was modeled in finite element software and the scheme of Figure 9 was reached. It is possible to notice that the highest stress reached was approximately 8MPa in the yellow section and the minimum stresses (in blue) at the ends, as suggests the normal stress distribution shown in Figure 1. Using the expressions suggested by NF EN 1337-3, (2006), for the shown loading of 4220kN, the maximum compression stress was given at 8.4MPa, which shows a proximity to the value found in the finite element model, with a difference of only 4.7%. The vertical maximum displacement shown in the software was approximately the same as that found using equation 1.

Figure 2 also shows that for a transversal section bearing (400mmx600mm) the load limit for leading the bearing to rupture is of 4690 kN. For this load value, the rupture occurred at a stress of 7.8MPa. Observing Figure 10, it can be seen that, using the MEF, this stress was 7.16MPa, with a difference of

8.2%. When analyzing the total vertical displacement for the same bearing and the same load, it is noted that using the analytical methods the displacement value is 4.78 mm, while using the MEF the displacement is 4.86 mm, with a difference of 1.64%.

When analyzing the bearing of dimensions (450mmx500mm) it is realized that the difference in stress between analytical methods and numerical methods is 1.96%, since the value shown in Figure 2 was 9.18MPa, and the one found in the software was 9MPa. For the total vertical displacement, this difference was 0.6%, since the value shown in Figure 2 was 4.92mm, and the one found in the software was 4.95mm.

Finally, a comparison was made between the results in the largest bearing investigated. For this bearing with dimensions of (425mmx725mm) it was necessary to extrapolate using the trend line of the curve, which showed that this rupture would occur only for a load of 9747,2kN. For this load, the maximum stress found using equation 1 is 11.16MPa. Using the MEF, this value is of approximately 12.3MPa, which gives a difference of 9.26%. For this same load using the numerical method model shown in Figure 12, the total displacement is 4.92mm, larger than that shown by the graph of Figure 5, which is limited by a load of 7890kN, less than that investigated. This shows the consistency between the two values when considering extrapolation of load values.

The graph of Figure 13 shows the behavior of these variations for all transversal sections investigated by comparing the two methods for rupture stresses and maximum displacement.

Fig. 9. (a) Compressive stress in MPa and (b) maximum distortion limit in mm for a bearing in reinforced neoprene of 400mmx500mm

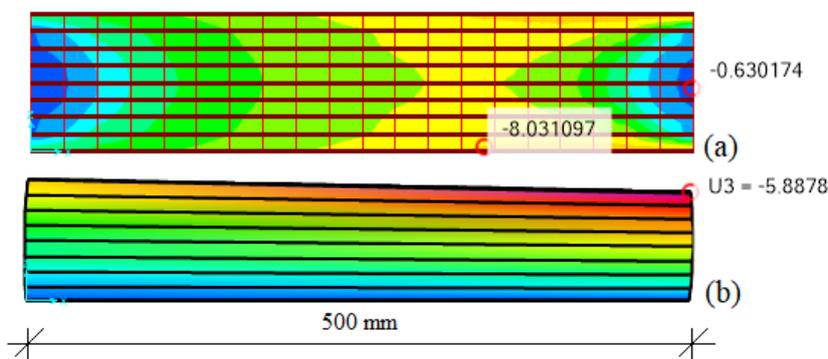


Fig. 10. (a) Compressive stress in MPa and (b) maximum distortion limit in mm for a bearing in reinforced neoprene of 400mmx600mm

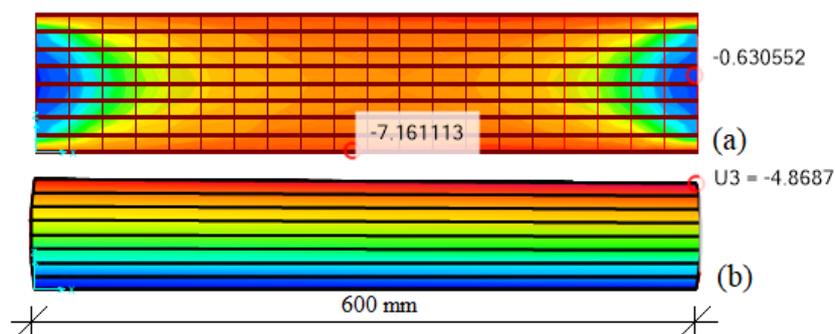


Fig. 11. (a) Compressive stress in MPa and (b) maximum distortion limit in mm for a bearing in reinforced neoprene of 450mmx600mm

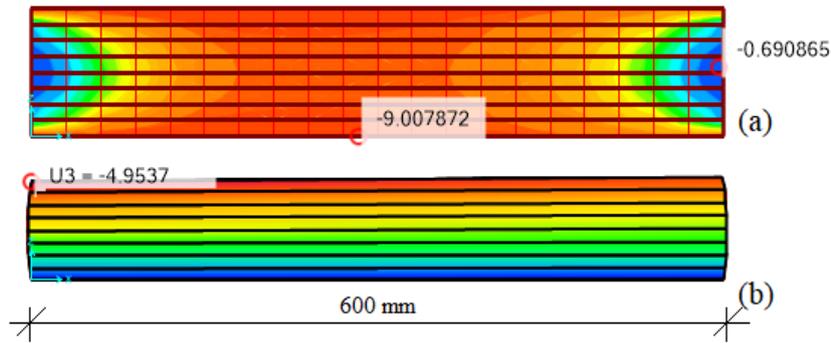


Fig. 12. (a) Compressive stress in MPa and (b) maximum distortion limit in mm for a bearing in reinforced neoprene of 475mmx725mm

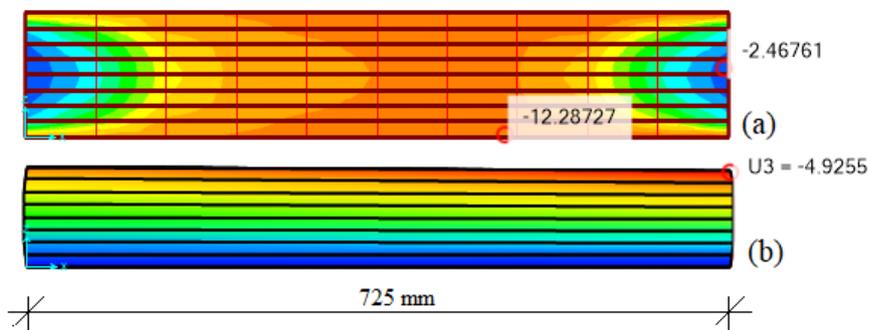
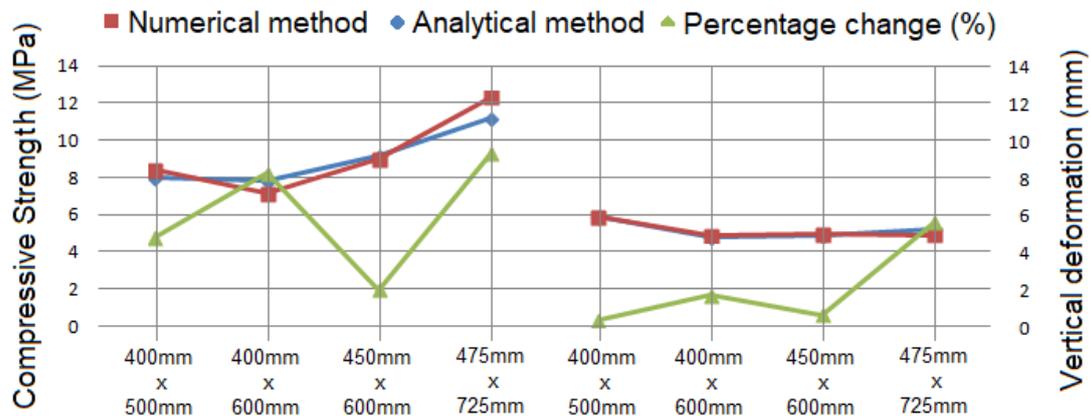


Fig. 13. Percentage variation between the two methods for stresses and deformation.



6 CONCLUSIONS

The bearings must be compatible with functions for which they have been designed, and must meet the various performance criteria imposed by the current standards. There are a lot of analytical parameters for the design of a bearing to be deployed.

The presentation of vertical loads, horizontal loads, stress, displacements, rotations and dimensioning aspects done along this work show the great amount of data that must be incorporated in a project of analysis and dimensioning of bearings.

The formulation used, combined with international standards, is a very important tool for analysis.

Symbolic algebraic computation has shown a wide variety of behaviors in the aspect of the workability of bearings in reinforced neoprene, and its proper choice rests with the designer, within the limitations of the design, to be done in an analytical and coherent way with the behavior that can occur in each situation.

Within the investigated parameters, it was observed that the values presented by the finite element method converge with the formulation presented by the standards, and there is not much distance between the results.

The investigation showed that the bearings that presented the highest range of workability were the charcoal neoprene of 475mmx725mm with a much higher elastic range compared to the others investigated. It is concluded that the transversal section area is a determining factor in the load capacity of the various investigated parameters.

Fig. 14. Working ranges of bearings

Reinforced elastomer 400x500 mm													
Reinforced elastomer 400x600 mm													
Reinforced elastomer 450x600 mm													
Reinforced elastomer 475x725 mm													
Load (kN)	460	1400	2340	3280	4690	5630	6570	7510	8450	9390	10330	11270	12210

ACKNOWLEDGMENTS

Not applicable

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