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Influence of eccentric load introduction during launching with rockers using an elastomeric bearing

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Abstract

During launching, the superstructure acts as a continuous beam supported by different launching bearings on the piers. Just before reaching the next pier, a part of the superstructure temporarily behaves as a long cantilever. As a result, a large bending moment and reaction force at the last bearing occur. The interaction of the internal forces results in a biaxial stress state in the cross-section. This load case is usually determining for the buckling check and the structural design of the webs. Additionally, the webs of the superstructure and the launching bearing often fail to share the same center lines. This eccentricity can be caused by misalignments of the launching bearings, the necessary air gap to the lateral guide as well as the different thicknesses of the panels along the superstructure. These eccentricities are not considered in the buckling check according to EN 1993-1-5 [1]. It is often discussed how these eccentricities affect the buckling behaviour and whether they must be considered in the buckling check. In the case of launching bearings like a rocker system which includes an elastomeric bearing between the superstructure and the launching beam, the reaction forces of the nonlinear material behaviour are additionally discussed. In [2] the effects on the buckling resistance in dependence of load eccentricity for some parameters for the different types of launching bearings are presented. [3] shows the comparison of the buckling resistance with investigations from [4] and [5] with the buckling check according to [1]. A comprehensive summary and the new proposal for considering an eccentric load application and clamping effects in the buckling zone can be read in [6]. This paper shows first investigations of the influence of the elastomeric bearing and the problem of the reaction of the nonlinear material behaviour and its definition in the numerical model. The results have shown that load eccentricities in combination with elastomeric bearings have no impact on the buckling behaviour.

Keywords

eccentric load introduction, buckling behaviour, steel bridges, incremental launching

1 Introduction

1.1 Imperfections and eccentricities during launching

Imperfections and eccentricities occur during launching because of unavoidable displacements between the system lines of the webs of the superstructure and the launching bearings (see Figure 1). Reasons for this are manufacturing tolerances, the movement of the system line of the web and the bottom plates of the superstructure (e_1) due to varying plate thicknesses over the length of the bridge, the necessary clearance to the lateral guide (e_2) during launching and installation tolerances for the position of the launching bearings (e_3). Figure 1 shows a typical cross-section of a box girder with the positioning of the lateral guiding and the launching bearings during launching. It schematically represents the composition of the displacements. In total ($e = e_1+e_2+e_3$), there is a misalignment of approximately 30 - 50 mm between the load introduction in the webs during the launching.

The influence of an eccentric load introduction on the bearing capacity of a longitudinally stiffened plate depends on the rotational degree of freedom φ_x of the launching bearing (see Figure 2). Without a possible rotation φ_x, an eccentric load introduction has no influence on the bearing capacity. In [6], these influences were analysed and described comprehensively.

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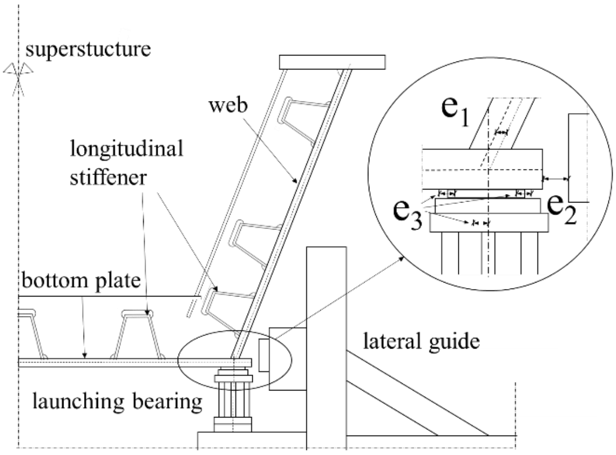

Figure 1 Eccentricities occurring at the launching bearing [2], [6]

1.2 Launching bearings

When incrementally launching large steel and steel composite bridges, two different types of launching bearings are usually used, namely launching rockers and hydraulic launching bearings. The use of hydraulic launching bearings has the great advantage of allowing continuous force regulation and transverse force redistribution by hydraulic pressure during launching. The launching beam rests on the hydraulic jack, on the top of which a spherical bearing is directly mounted. The spherical bearing allows free rotation in all directions. Additional lateral guides by steel plates are provided next to the jack to limit the movements, but small rotations are possible. This can lead to a rotation φ_x in the transverse direction of the bridge. Therefore, eccentricities are introduced into the web of the superstructure, where they cause out-of-plane bending of the web. If the bottom plate is not stiff enough to resist these eccentricities, the buckling behaviour can be negatively affected. Figure 2 shows the schematic structure of a hydraulic launching bearing system.

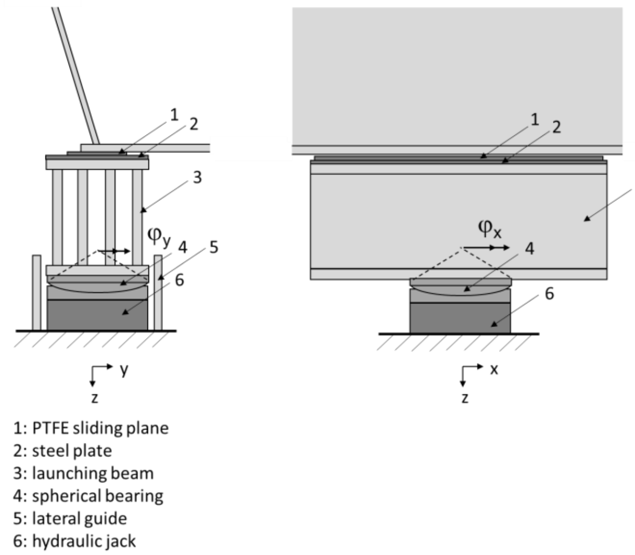

Figure 2 Hydraulic launching bearing [2], [3], [6]

The launching rocker only allows a rotation φ_y in the longitudinal direction of the bridge, while it is linearly supported in the transverse direction. The bending due to the eccentricities is resisted by the launching bearing itself if it has sufficient torsional stiffness and tilting of the structure can be excluded. However, this also means that no load balancing is possible in the transverse direction, e.g., in the case of curved bridges. To compensate stress peaks in the longitudinal direction, elastomers are attached to the launching beam of this bearing type. In the context of the eccentric load introduction in transverse direction of the bridge, it is discussed for practical application whether this elastomer influences the buckling behaviour of the web and if it should be considered in the numerical model for the buckling verification. Figure 3 shows the schematic structure of a launching rocker system.

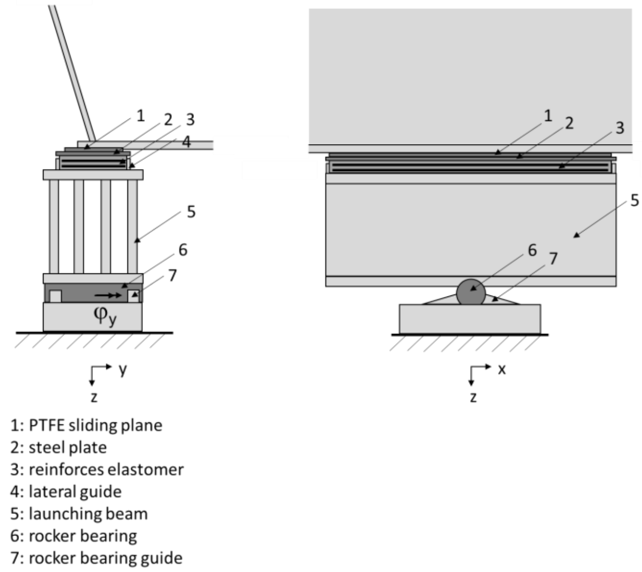

Figure 3 Launching rocker system [2], [3], [6]

1.3 Material characteristics of elastomers

Reinforced elastomeric bearings consist of elastomer layers which are strengthened by steel plates and surrounded by elastomer cover layers. In a vulcanization process, the individual components of this type of bearing are joined together to form a single component. This leads to a lateral strain limitation of the single layers and thus to an increase in vertical stiffness and bearing capacity.

The fundamental understanding of such bearing behaviour was developed independently by Conversy [7] and Topaloff [8]. The verifications and boundary conditions derived from their approaches can be found in the standard DIN EN 1337-3 [9]. The material behaviour of elastomers bearings depends in particular on temperature, load speed, load amplitude, load repetition, load direction, load distribution and shape factor, so that these materials exhibit very complex behaviour. For the development and formulation of material laws and their description with mathematical models, the knowledge of the mechanical properties of the material structure under the mentioned influences and their effect on the deformation behavior is fundamental. Since elastomers, like liquids, are almost incompressible (transverse contraction coefficient $\mu \approx 0.5$), i.e., deformations occur under almost constant volume, the material behaviour is predominantly characterized by the shear stiffness.

The forces (restoring forces F_R) and moments (restoring moments M_R) acting on the structure because of the elastic deformation of the elastomer are of elementary importance for the design of the adjacent constructions and individual bearing components. Restoring moments can lead to gapped joints if the resultant load is outside the core of the bearing base surface.

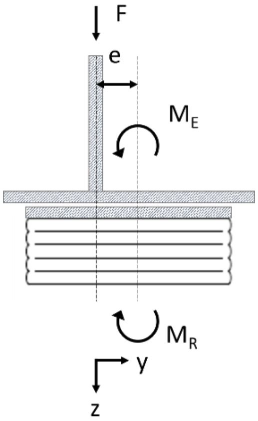

Figure 4 Moments from eccentric loading and material behaviour

In the case of an eccentric load, as it occurs in the investigated cases of load introduction during the launching of bridges, the restoring moment from the nonlinear material of the elastomer has a positive effect on the buckling behaviour. The compression modulus of elastomers depends, among other things, on the load. This means that the material response is stiffer in areas subjected to higher loads than in areas with lower loads, which is also the reason for using it during launching. It should compensate for irregularities by uniform load introduction. This material behaviour results in a restoring moment (M_R) in response to rotation. It counteracts the resultant moment (M_E) from the eccentric load (see Figure 4) and centers the load over the web.

2 Consideration of the elastomeric bearing in FEM

The general modelling of the plate with its boundary conditions and the recalculation of the tests to validate the numerical model are shown in [2,3,5 and 6].

The influence of the eccentric load introduction on the buckling behaviour of the web results primarily from the possibility of flange rotation. Flange rotation is not possible in the launching rocker system because the flange is clamped in the launching beams and these do not rotate by φ_x due to the support via rocker bearings. However, we and other civil engineers working in the sector of bridge construction suspected that a soft elastomer, for example, could also cause rotation of the flange in this type of launching bearing. Also, the effect of the restoring moment from the material response was not investigated.

Therefore, two approaches were used to consider the elastomer:

1. modelling of linear countersunk springs with calculated equivalent stiffness according to [9].

2. modelling of an elastomer with nonlinear material definition.

When modelling countersunk springs, the existing restoring moment from the nonlinear material behaviour is neglected. This should have a greater effect on the rotational sensitivity φ_x of the system. This assumption is thus on the conservative side for modelling the effects from eccentric load introduction. The second approach was chosen to identify influences that may arise from the nonlinear material behaviour.

2.1 Modelling of linear counter sunk springs

For the buckling analysis, the model investigated in [6] is used and modified slightly. Simple countersunk springs are added to the FE model to consider the elastomer layer between the launching beam and the superstructure. Also, a 20 mm thick plate is added on top of the countersunk springs, as shown in Figure 5. This plate is needed to avoid local deformation of the superstructure into the elastomer and serves as a sliding plane. In the model, the plate is also needed to define the contact with the friction and penetration there. The springs act only in the z-direction with a given spring constant. Shear forces in the x and y directions are transmitted by this contact. In order not to introduce the loads in the z-direction via the contact elements, very large indentation tolerances are specified for these elements. The correct load introduction can be checked based on the determined spring forces. More detailed information on the calculations and models can be found in [6,10].

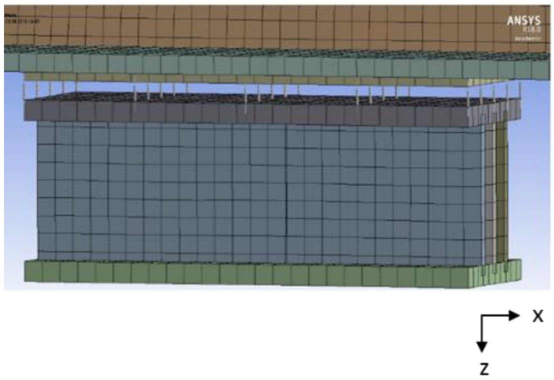

Figure 5 Modelling of the rocker bearing using countersunk springs [10]

The spring constant is determined by the sum of the vertical deformations according to the following equation:

$$v_c = \sum \frac{F_z \cdot t_i}{A'} \cdot \left(\frac{1}{5 \cdot G \cdot s_1^2} + \frac{1}{E_b}\right) \quad (1)$$

with:
F_z = design value of vertical forces
t_i = thickness of a single elastomer layer in a reinforced bearing
A' = effective base area of a reinforced elastomeric bearing (area of the steel plates)
G = nominal value of the ideal shear modulus of an elastomeric bearing
s_1 = shape factor for the thickest inner layers
E_b = compression modulus

For the assumptions of the dimensions, real elastomeric bearings are used whose blueprints are available.
Since no further information on material data is available, assumptions are made according to the bearing standard

DIN EN 1337-3 [9]:

- Reinforced elastomeric bearing type B with 3 reinforcement layers.
- Shear modulus G = 0.9 MPa
- Compression modulus E_{BT} = 2000 MPa

Using the equation from DIN EN 1337-3 [9], the vertical deformation paths of one elastomeric bearing can be approximated, and a spring constant can be determined from this.
The spring constant k_{tot} = 6226943 N/mm refers to the elastomer surface with external dimensions of 750 mm by 268 mm. To generate a load introduction that is as uniform as possible and corresponds to a realistic elastomer, a total of 25 countersunk springs are modeled on this surface. The spring constants are reduced according to the proportion of the load introduction surface relative to the total surface.
The high stiffness of the elastomer results, on the one hand, from the fact that the material behaves almost incompressible [11] and, on the other hand, from thickness of only 32 mm and 3 reinforcing layers of the elastomer. Since thicker elastomers are also used for rockers in practice, a parametric study is carried out. Here, the calculated stiffness is reduced to 10% and 1%. The reduction to 10 % would correspond to a bearing with a 16 cm high but unreinforced elastomer pad. The investigated case of 1.0 % is a purely theoretically determined value and does not occur in practice. Only for this case, a load reduction of 1.6 % is determined for an eccentricity of the load e = 30 mm. The results of the bearing capacity are shown for all three spring stiffnesses for the cases e = 0 mm and e = 30 mm in the following Table 1. The total deformation is shown for k = 1 % and e = 30 mm in Figure 6. A small rotation of the flange can be observed. For the practical range of bearing stiffnesses, no influence of the load eccentricity is observed.

Table 1 Bearing capacity with different spring stiffnesses

	$K_{tot.}$ (100%) = 6226943 N/mm	**$K_{tot.}$ (10%) = 622694,3 N/mm**	**$K_{tot.}$ (1%) = 62269,43 N/mm**
e [mm]	**Fz [kN]**	**F_z [kN]**	**F_z [kN]**
0	1788,5	1788,5	1788,6
30	1788,5	1788,5	1760,5

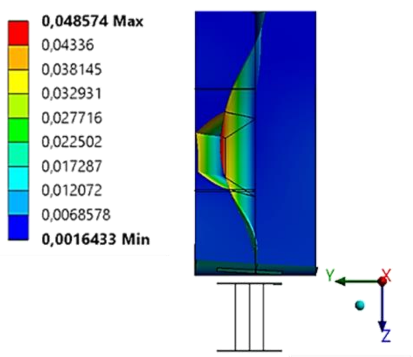

Figure 6 Web buckling and flange rotation using countersunk springs with 1 % of the usual elastomer stiffness in praxis [6]

2.2 Modelling of an elastomer with nonlinear material behaviour

In the process of extended investigations of an influence of the nonlinear material behaviour of the elastomeric bearing on the buckling behaviour, a model with hyper elastic material behaviour according to Arruda-Boyce [12] was developed. The model was verified in a first step according to [11]. In this work, the torsional resistance of reinforced elastomeric bearings was investigated. Tests in [11] were carried out, loaded with a maximum centric compressive stress of 1 N/mm² and a rotation of 0.1% (0.56°). The material data of the uniaxial and biaxial tests from [11] were used for the verification. This is a hyper elastic material model suitable for considering nonlinear properties, such as the generation of restoring moment. Since the investigations involved static loading, the Bergström viscoelastic material model was not modelled. The "curve fitting" according to Arruda-Boyce is performed with the first load path of the test data. The calculation is performed on the same geometry of the specimen from [11].

According to [11], the second load path was used for the numerical recalculations. Since the elastomer reacts more rigid under repeated loading, the restoring moment is correspondingly smaller than in [11]. Similarly, when the Arruda Boyce material model is selected, the loading speed is not considered, which affects the material response. However, since the resulting restoring moment is understandable and on the conservative side, this material definition is applied to the full model to investigate plate buckling. The elastomer was inserted into the plate model to investigate the influence on buckling. For this purpose, several pads were lined up along the length of the rocker. That corresponds to the realization of rocker constructions in practice. Identical to the spring model, a steel plate was inserted between the superstructure and the elastomer. A buckling analysis with e = 30 mm is carried out and the result of the bearing capacity is compared to the model without an elastomer, whereby no difference can be seen.

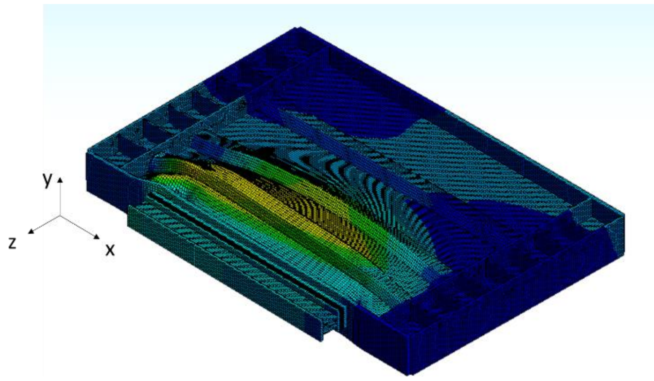

Figure 7 Plate buckling using an elastomer including nonlinear material for e =30 mm [6]

This can be explained by different reasons. On the one hand, only one elastomer was investigated, it may have been modelled too rigidly to be able to detect the effect. On the other hand, for the reasons already discussed and described in more detail in [6], there is only a small influence of the eccentric loading, if in fact at all. However, further investigations will not be carried out at this point.

For the cases investigated, no influence of the elastomer can be detected due to the eccentric load introduction in the transverse direction. Further investigations would be too extensive and would only exceed the time limits of a calculation for practical applications. A simplified parameterization is not expedient at this point, as described in the following.

3 The difficulties of the nonlinear material definition

Several barriers exist in the interpretation of numerical results. The experimental data from [11] go up to a pressure range of -1 N/mm², by extending this by means of curve fitting a range up to -3 N/mm² is covered. Since this pressure range is too small for the intended calculations, the material curve must be fitted using the parameters of the Arruda-Boyce method [12]. The material curve is shown in Figure 8. The thick blue line is obtained from the uniaxial test data, and the thick red line is obtained from the biaxial test data from [11]. The thin lines are obtained by curve fitting using the Arruda-Boyce model using [13].

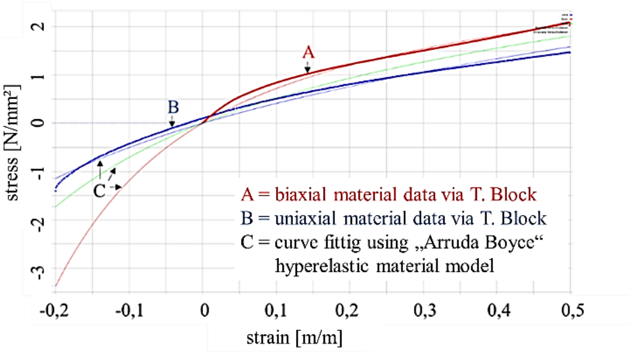

Figure 8 Material definition for the elastomer in FEM [13]

The elastomer reacts as a function of the load repetition and the load speed. In the nonlinear analysis, load steps are defined in which the load is increased. A loading speed is not defined. The strain hardening behaviour therefore does not correspond to the real situation during launching. For a hyper elastic material model, a definition of several elements over the thickness is required. Since the steel plates in the elastomers are very thin, a fine mesh is required, resulting in many elements and thus extremely long computation times. Hyper elastic material models often lead to numerical problems when modelling sharp edges. The edges of elastomers have therefore been rounded, but the geometry has an impact on the results, as exemplary studied in [11].

It is unclear whether elastomers respond to eccentric load introduction in the same way as they do to rotation. According to [], bearings are tested according to Annex J over a defined angle of rotation. However, due to the nonlinear material behaviour, the relationship F * e = M is not necessarily equal to the applied rotation. This should be investigated systematically with experimental tests. A parameterization of the model with influences on the response of the material of the load speed and repetition, with changes of the geometry due to different displacement bearing lengths at the same time, is enormously complex and computationally intensive. In the calculations, not only the results must always be questioned, but also the assumptions made and their interaction with other parameters. Modelling of the elastomer is therefore not recommended for a practical structural calculation.

4 Summary

Based on the presented investigations and the investigations in [6], it can be concluded that the influence of the elastomer in the transverse direction of the bridge can be neglected in the buckling analysis. Nonlinear material effects from the elastomer have a positive effect on the buckling analysis since the acting moments from the eccentric load are compensated. Neglecting the nonlinear material behavior, an investigation was carried out on the conservative side with linear springs. These results also show that the elastomer can be neglected. Only when a standard elastomer is reduced to 1% of its usual stiffness a small rotation of the flange can be observed. The bearing capacity is then reduced by 1.6%. Elastomers with such stiffness are not used for in the civil engineering sector. An eccentric load application in the transverse direction can therefore be neglected when shifting bridges using launching rocker systems.

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