

ПОДХОДИ ЗА МОДЕЛИРАНЕ НА СТОМАНОБЕТОННИ КОЛОНИ, ПОДЛОЖЕНИ НА УДАР ОТ ПРЕВОЗНИ СРЕДСТВА

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DESIGN APPROACHES FOR MODELLING OF REINFORCED CONCRETE COLUMNS SUBJECTED TO VEHICULAR IMPACT

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Abstract:

The precise modelling of vehicular impact or its corresponding impulse load, applied to a structure is of great importance in the field of structural engineering. There are various methodologies for calculating impact effects outlined in the Eurocodes. This paper aims to critically evaluate and compare alternative modeling approaches to assess their accuracy. Specifically, this study provides a comprehensive comparative analysis between standard Eurocode requirements and a refined dynamic model incorporating concentrated mass, axial stiffness (spring), and damping elements.

These methodologies are implemented on a concrete column from a bridge pier, which is modelled as a Multi Degree of Freedom (MDoF) system with distributed mass to capture the complex effects during a collision. The research focuses on the time-history response and the distribution of internal forces within the pier. The findings from these analyses provide essential insight into which approach presents more conservative results for structural design and long-term safety. By examining the peak displacements and base moments generated by each model, the study determines whether alternative analytical procedures can be integrated into professional practice as a supplement to current regulatory standards. Ultimately, the results suggest that adopting more sophisticated dynamic models may lead to more cost-effective and robust engineering solutions, offering designers a more detailed understanding of structural behavior under extreme loading conditions.

Keywords:

Dynamics, Impact, Eurocode, Reinforced Concrete Column, Modelling, Spring, MDoF

1. INTRODUCTION

In structural engineering, impulse loading represents a critical category of dynamic action where a high-magnitude force is applied over an extremely short duration. Unlike static loads,

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where the structure reaches an equilibrium state, impulse loads trigger a transient response where inertia play dominant roles. As highlighted in the seminal works of Chopra,[1] and Clough & Penzien, [2], the structural response to such accidental actions is governed not just by the peak force, but by the relationship between the load duration (t_d) and the natural period of the structure (T).

An impulse is mathematically defined as the integral of force over time.

In the context of Single Degree of Freedom (SDoF) systems, if the duration is less than half the natural period ($t_d < 0,5T$), the maximum displacement is primarily a function of the total impulse (the area under the force-time curve) rather than the specific shape of the pulse. This simplifies the analysis into a "pure impulse" scenario where the load imparts an instantaneous initial velocity to the mass, converting kinetic energy into potential strain energy.

For Multi Degree of Freedom (MDoF) structures, the complexity increases. Accidental actions, such as explosions or vehicular impacts, often excite higher vibration modes that are usually negligible under seismic or wind loads. Chopra, [1] emphasizes that the Dynamic Load Factor (DLF) – the ratio of dynamic to static displacement – can reach values as high as 2.0. This means that a structure may experience stresses twice as large as those predicted by a static analysis of the same peak force.

The study of impulse loads is vital for preventing progressive collapse. When an accidental impact occurs (e.g., a column being struck), the structure must possess enough ductility and redundancy to redistribute the suddenly applied energy. Modern safety standards require a "damage-tolerant" design, where the dynamic analysis accounts for strain rate effects, energy dissipation and nonlinear behaviour.

2. THEORY

2.1. Dynamic impact design according to Eurocode – BDS EN 1991-1-7, [3]

Based on the guidelines in [3], an impact occurs when a moving object strikes a structure, causing its kinetic energy to be abruptly converted into deformation energy. To accurately calculate the resulting dynamic interaction forces, one must understand the mechanical properties of both the moving object and the target structure. While equivalent static forces are common in standard design, modern structural analysis often incorporates more complex factors like dynamic effects and nonlinear material behavior.

According to the classification system in Appendix C of [3], impacts are categorized as either "hard" or "soft" based on how energy is absorbed.

2.2. Hard impact, [3]

Under the Eurocode framework, a hard impact is defined by the assumption that the structure remains rigid and fixed while the striking object undergoes linear deformation.

The peak dynamic interaction force F , is calculated by the formula

$$F = v_r \sqrt{km}. \quad (1)$$

where v_r is the object's velocity, m is object's mass, and k its equivalent elastic stiffness.

This interaction is typically modelled as a rectangular pulse applied to the structure's surface. The duration of this pulse (Δt) is determined by the relationship

$$\Delta t = \sqrt{m/k}. \quad (2)$$

representing the momentum transfer:

$$F\Delta t = mv. \quad (3)$$

For scenarios where the impacting object is represented as a uniform cross-section, its physical properties are calculated as follows:

$$k = EA/L. \quad (4)$$

$$m = \rho AL. \quad (5)$$

where: L is the length of the impacting object; A is the cross-section area; E is the modulus of elasticity; ρ is the mass density of the impacting object.

These equations allow engineers to translate the physical dimensions and material properties of a vehicle or object into a quantifiable impact load for structural analysis.

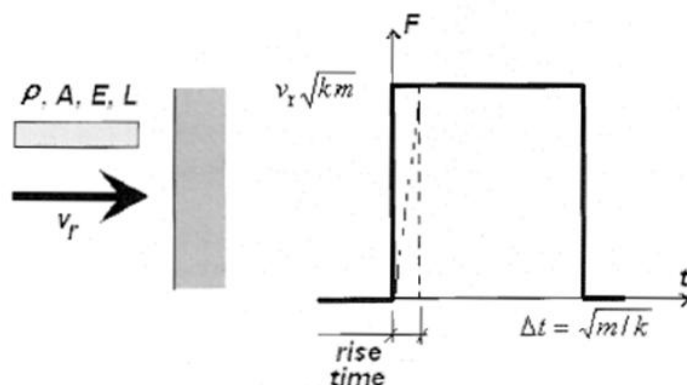


Figure 1. Impact model, F – dynamic interaction force, [3]

2.3. Soft impact, [3]

The Eurocode defines a soft impact as a scenario where the structure is treated as elastic while the striking object is assumed to be rigid. In this case, the same mathematical framework used for hard impacts can be applied, provided that the stiffness value (k) is replaced with the specific elastic stiffness of the structure itself.

If the design strategy relies on the structure absorbing the hit through plastic deformation, the material must possess enough ductility to fully dissipate the object's total kinetic energy $1/2mv_r^2$. In a "limit case" involving a rigid-plastic response, the structure's capacity must meet the following energy-balance condition:

$$\frac{1}{2}mv_r^2 \leq F_o y_o. \quad (6)$$

where: F_o – is the plastic strength of the structure, i.e. the limit value of the static force F ; y_o – it its deformation capacity, i.e. the displacement of the point of impact that the structure can undergo.

3. MODELLING APPROACH

3.1. Object modelling specifications

A reinforced concrete column from a bridge pier is considered. The pier consists of four columns. Each column has circular cross-section with diameter 100 cm. The columns are designed and made from concrete with class C 35/45 with compressive strength – $E = 34$ GPa, according to BDS EN 1992-1-1:2005, [4], table 3.1 – Strength and deformation characteristics for concrete. The column height is 515 cm.

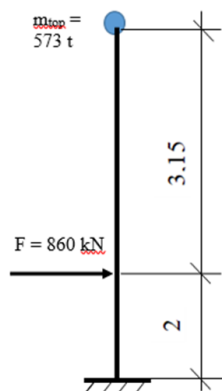


Figure 2. Concrete column design.

The ANSYS Mechanical APDL software is used to design the column.

3.2. Impact design according to Eurocode procedure – model with impulse load function

The column is modelled with the element BEAM188. BEAM188 is a versatile, two-node 3D beam element in ANSYS based on Timoshenko beam theory, designed for modeling structures ranging from thin to moderately thick. It supports linear to cubic interpolation, includes six or seven degrees of freedom per node, and is suitable for nonlinear analyses involving large deflections, plasticity, and creep.

The whole column is designed with distributed mass. The mass on the top of the structure is modelled with the element MASS21. Its value m_{top} is calculated to correspond to the maximum vertical load from the bridge superstructure – 5620 kN, i.e.:

$$m_{top} = 5620 / 9,81 = 573 \text{ t} \quad (7)$$

The impact force is applied to an area which is 2 m above the foundation level. The mass from the vehicle is 20 t and the velocity is 40 km/h, according to [3]. The equivalent elastic stiffness of the object is $k = 300 \text{ kN/m}$, [3]. The impact force F and the impulse duration Δt are calculated as follows:

$$F = v_r \sqrt{km} = \frac{40 \cdot 1000}{3600} \cdot \sqrt{\frac{20000}{1000}} \cdot 300 = 860,66 \text{ kN} \quad (8)$$

$$\Delta t = \sqrt{m/k} = \sqrt{\frac{20000/1000}{300}} = 0,2582 \text{ s} \quad (9)$$

It is assumed to be a rectangular shape of the loading impulse [3] as shown on Fig.3.

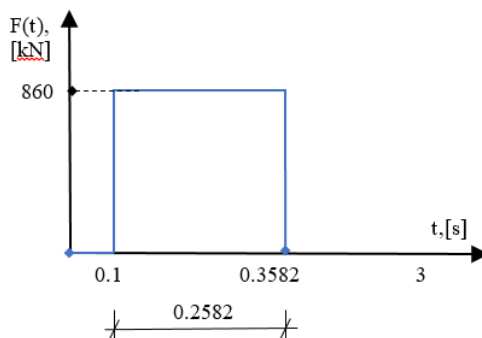


Figure 3. Impulse load function

3.3. Impact design according to Eurocode procedure – model with spring and damper

In this approach the column is again modelled with the BEAM188 and MASS21 elements. The structural geometry and material properties are identical to those of the previous model. The distinguishing feature in this configuration is the attachment of a spring with stiffness $k = 300$ kN/m, attached to it mass – $m = 20$ t, calculated according to Eurocode requirements and a damper with stiffness $c = 5000$ kNs/m. This spring–mass–damper system configuration is attached to the column at the impact level of 2.0 m.

The objective of this modeling approach is to simulate a realistic impact scenario where the vehicle ceases to exert force on the structure following the conclusion of the primary excitation.

The numerical simulation was performed using ANSYS Mechanical APDL. To achieve the desired behavior, a two–step analysis was executed utilizing the "Birth and Death" element technique:

Phase I: The damping element is deactivated (suppressed), allowing the spring and its associated mass to impact the structure.

Phase II: When the vehicle velocity drops to zero, the spring is deactivated simulating the end of the impact phase. At that same time the damper is activated to stop the motion of the spring–mass system.

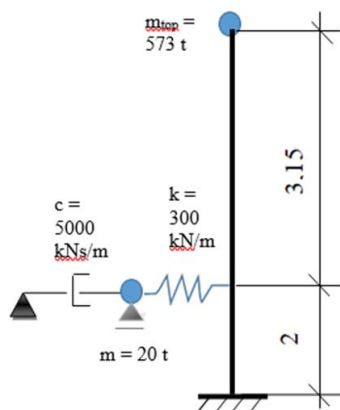


Figure 4. Spring – damper impact column model

4. RESULTS

The obtained deformed configuration and displacement contours of the column resulting from the dynamic impact analysis are illustrated on Figures 5-8. Based on the ANSYS Mechanical APDL output, the following key observations can be made:

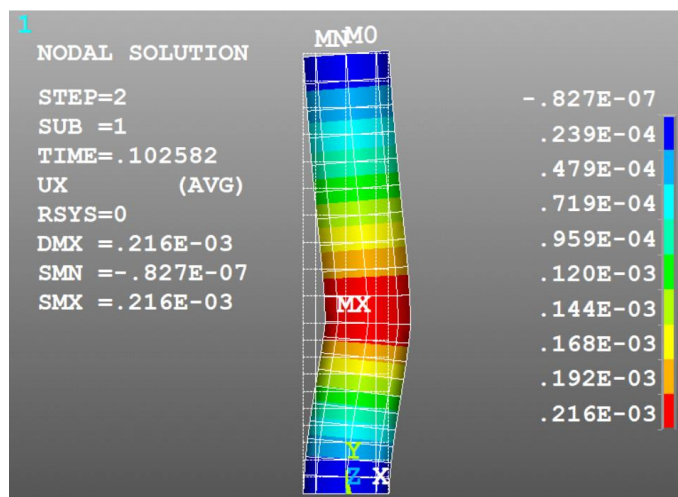


Figure 5. Deformed shape at the time $t = 0.1025$ s on the model with the impulse

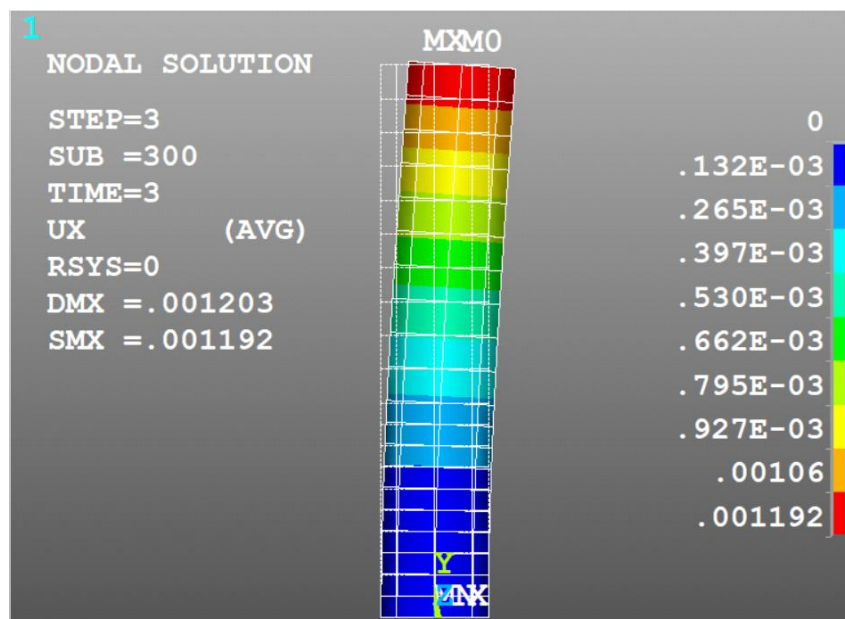


Figure 6. Deformed shape at the time $t = 3$ s on the model with the impulse

About the deformation profile: the contour gradient clearly identifies the zone of maximum displacement (highlighted in red) located at the 2.0 m impact elevation. The observed flexural behavior is consistent with the structural response expected for a vertical element under localized dynamic loading.

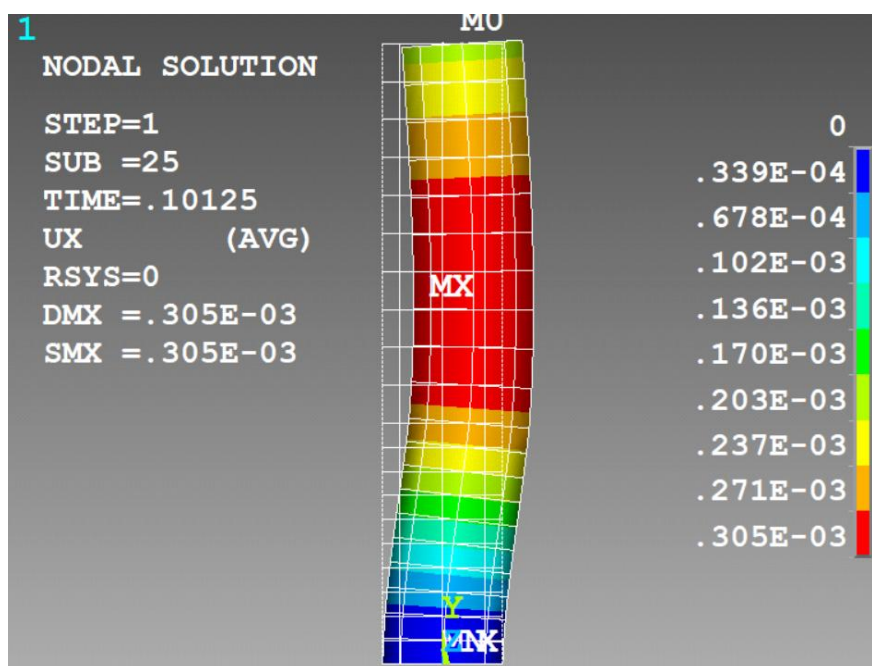


Figure 7. Deformed shape at the time $t = 0.10125$ s on the spring–damper model

The peak displacement value is recorded at $0,304 \times 10^{-3}$ m. The high level of correlation in displacement values between the impulse – based and spring – mass models confirm the adequacy of the modelling methodology and the accurate representation of mass and stiffness characteristics.

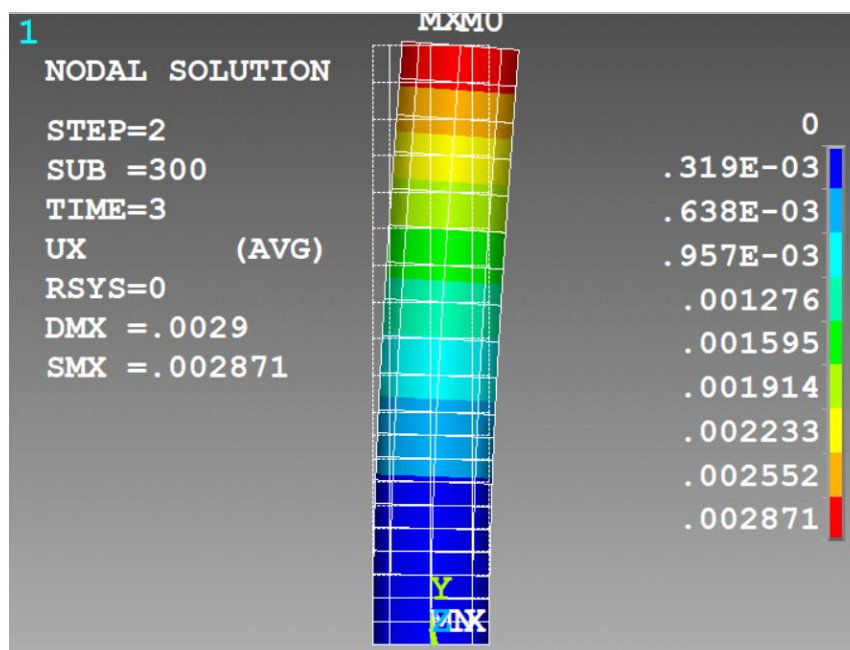


Figure 8. Deformed shape at the time $t = 3$ s on the spring-damper model

The visualized state captures the peak response during the simulation. The implementation of the "Birth and Death" procedure effectively captures the transition from forced excitation to free vibration. The results demonstrate that upon completion of the impact phase (Step 1) and the subsequent activation of the damper (Step 2), the structure successfully transitions into a free vibration regime, effectively isolating the residual influence of the vehicle mass.

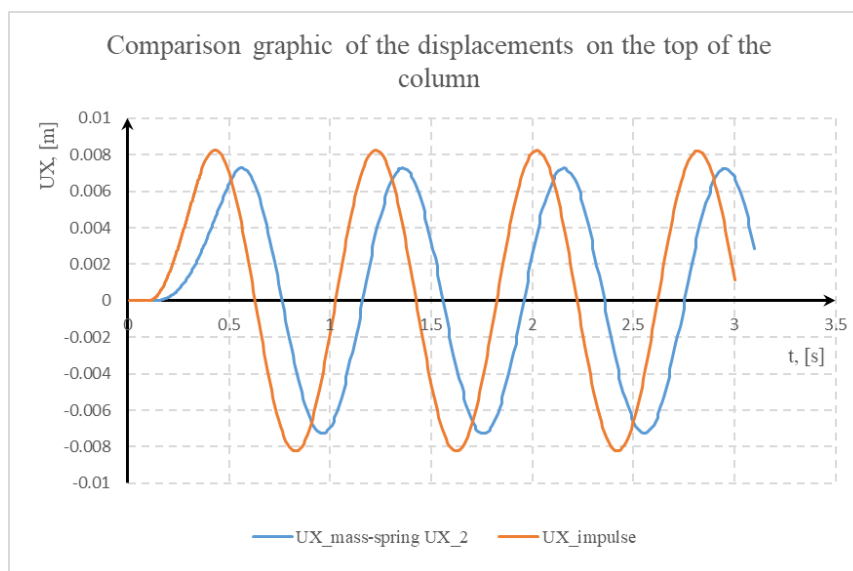


Figure 9. Comparison graphic of the displacements on the top of the column

The displacements results, from the Time history analysis, at the column top reveals a high level of convergence in peak magnitudes, with both models reaching approximately 0,008 m. A distinct temporal lead is observed in the impulse – driven model. Due to the instantaneous nature of the force application, it reaches its peak response approximately at 0,1 s earlier than mass–spring model. In the mass-spring configuration, the initial delay represents the time required for the spring to compress and transfer the kinetic energy to the structure. Following the initial

impact, both models transition into identical harmonic vibrations, confirming that the fundamental frequency of the structure is consistently modeled across both methodologies.

The base moment of the Time history analysis highlights more significant differences in the transient response phase. The impulse model (orange) exhibits a sharp, high frequency initial peak, reaching nearly 2500 kNm.

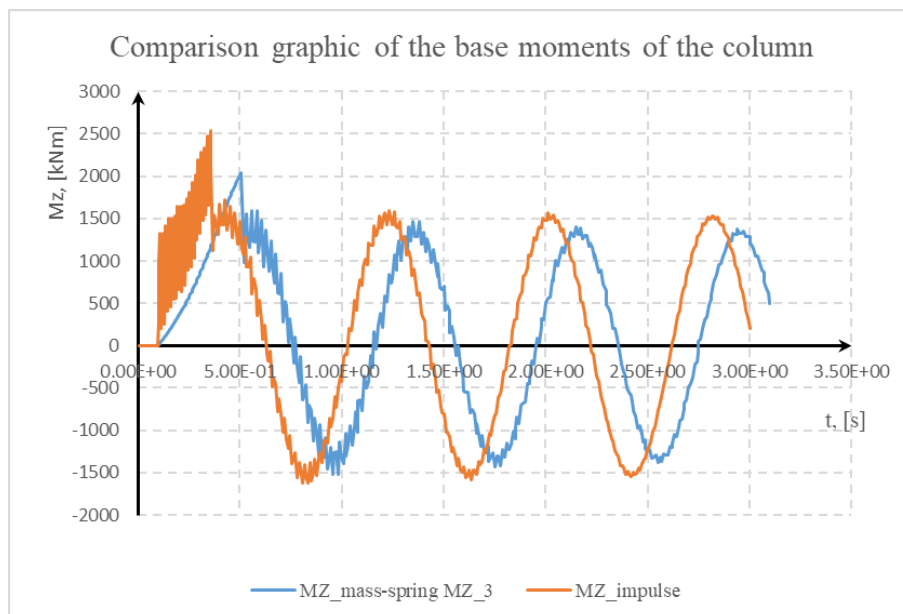


Figure 10. Comparison graphic of base moments of the column

This is characteristic of direct impact modeling without the effects of a spring–damper system. The mass–spring model (blue) provides a more regularized and physically realistic response.

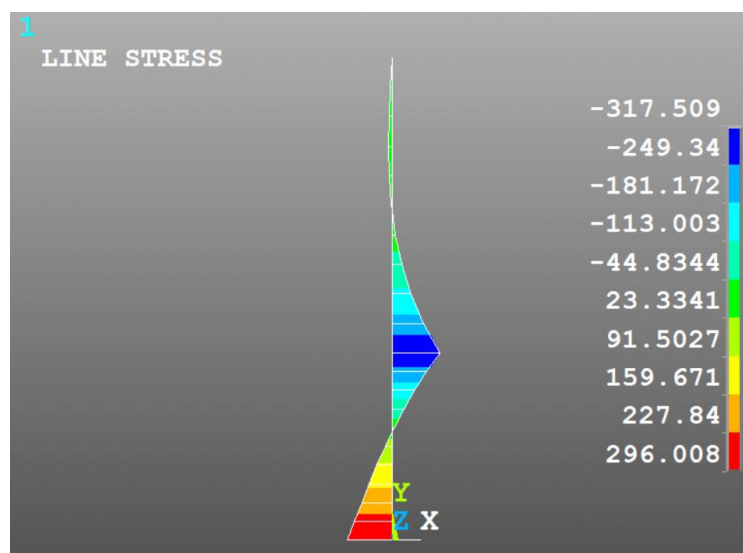


Figure 11. Moment diagram at the moment of impact on the model with the impulse

While the initial peak is slightly lower (approx. 2000 kNm), the model accurately captures the energy dissipation and force distribution prescribed by Eurocode. Despite the initial differences, both models settle into a sustained oscillatory state with peak moments of roughly ± 1500 kNm.

The phase shift identified in the displacement analysis remains constant here, with the impulse model consistently leading.

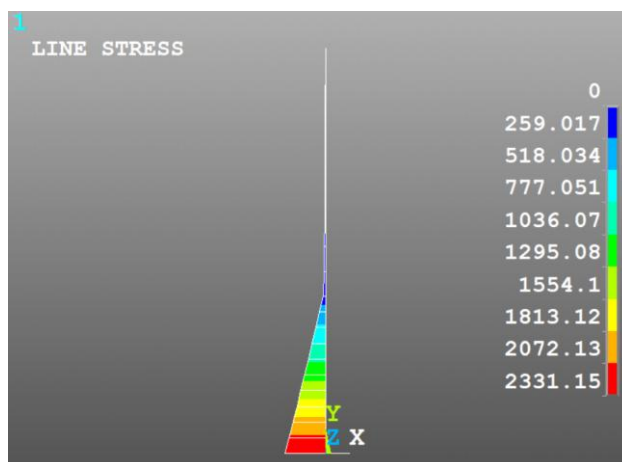


Figure 12. Moment diagram after the impact on the model with the impulse

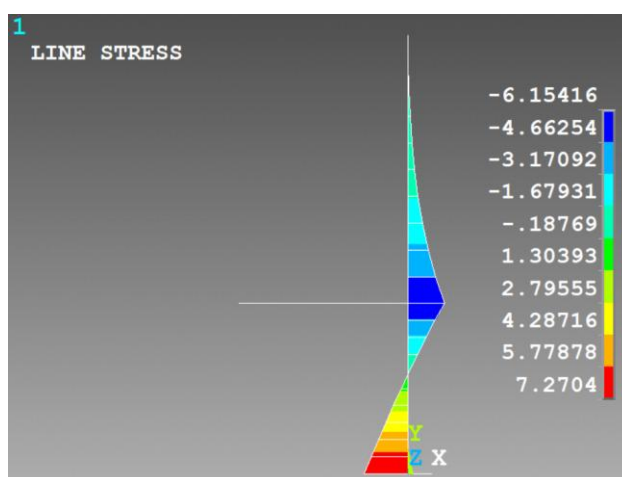


Figure 13. Moment diagram at the moment of impact on the spring-damper model

While displacement results remain comparable across both models, the approximately 25% increase in bending moments observed in the Eurocode – compliant spring model underscores the importance of this approach for a more conservative and robust structural design against impact loads.

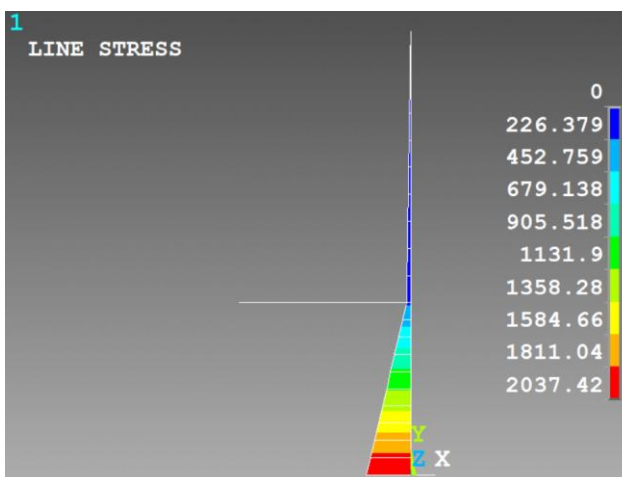


Figure 14. Moment diagram after the impact on the spring-damper model

5. CONCLUSIONS

During the impact phase, a pronounced peak in the maximum bending moment occurs upon the end of the impulse. This sudden escalation is attributed to the instantaneous dissipation of the applied force to zero, in accordance with the rectangular pulse duration model prescribed by Eurocode standards.

Regarding the peak displacement at the top of the structure and the bending moments at the base, the results derived from the Eurocode – compliant approach demonstrate only slightly elevated values compared to the model proposed in this study following the end of the impulse. This minor divergence suggests that while both models align closely in their post – impact predictions, the standard rectangular pulse model tends to produce a more conservative estimation of the structural response.

Despite the structure being modeled with uniform stiffness and mass, the peak responses occur at different temporal points following the onset of the excitation. It is observed that the impulse – driven model reaches its maximum values ahead of the spring–mass model.

Regarding displacements, both models present comparable results, making further refinement unnecessary.

Regarding bending moments, the Eurocode model presents values up to 25% higher upon the conclusion of the excitation compared to the spring–based model.

The "Birth and Death" technique applied to the mass-spring-damper system successfully simulates the vehicular impact and the subsequent termination of the contact/interaction between the structure and the vehicle.

While displacements remain comparable (suggesting that simplified models are sufficient for serviceability checks), the divergence in base moments suggests that the Eurocode – compliant spring–mass approach is more suitable for detailed stress analysis and conservative design of the column base and foundation.

The spring–mass–damper model provides a more robust representation of a real-world impact scenario by avoiding non–physical force spikes while maintaining the necessary structural demand for safety assessments.

ACKNOWLEDGEMENT

The authors gratefully acknowledge “Ponto” LTD team and especially eng. Miroslav Patrikov for providing access to the information required and used in this study. This work would not have been possible without their cooperation and resources.

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