

Simulation-Driven Design of Guardrail Structural Spacers: Influence of Geometry on Impact Response

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Simulation-Driven Design of Guardrail Structural Spacers: Influence of Geometry on Impact Response

Michele Cali^{1*}, Giuseppe Laudani¹, Giuliana Baiamonte¹, Gianfranco Di Martino¹ and Sebastiano Magnano¹

Abstract

The dynamic performance of road restraint systems is strongly influenced by the local behaviour of structural spacers, whose role is sometimes simplified or neglected in impact analyses. In particular, the spacer geometry governs load transfer paths and the localization of deformations, with direct effects on the global dynamic response of the barrier. In this study, the effect of spacer geometry on the impact behaviour of a steel guardrail system is investigated by means of an explicit finite element model, validated against experimental acceleration time-histories acquired from full-scale crash tests. Two spacer configurations are considered: a conventional solution and a rhomboidal geometry analysed under identical impact conditions to isolate the effect of spacer topology on the structural response of the system. In addition to the numerical assessment of deformations, stresses, and performance indicators, the study includes an analysis of manufacturing considerations, highlighting the compatibility of the proposed geometry with industrial cold sheet metal forming processes and a design for manufacturing approach. The results show that the rhomboidal configuration promotes a more controlled deformation behaviour, limiting the propagation of deformations along the barrier and producing a more regular overall dynamic response, while remaining compatible with conventional sheet-metal manufacturing. The proposed approach provides an integrated design- and manufacturing-oriented framework for the evaluation of spacer geometries in road restraint systems.

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1 Introduction

Road safety barriers are a fundamental element for the safety of transportation infrastructures, as they are designed to contain out-of-control vehicles and reduce the severity of consequences for occupants during an impact. Numerous studies have demonstrated that the adoption of properly designed containment systems enables a significant reduction in the risk of severe and fatal injuries, particularly in contexts characterized by high travelling speeds and critical geometric conditions, such as mountainous road sections and highways [1,2,3,4].

Within the European context, the design and performance verification of road restraint systems are

regulated by the EN 1317 standard, which defines containment classes, test scenarios, and acceptance criteria for the evaluation of the dynamic behaviour of barriers. This regulatory reference constitutes the baseline framework for the development of design solutions capable of ensuring high levels of safety and operational reliability, while providing limited guidance on the influence of individual structural components on the local and global dynamic response of the barrier [5].

In recent years, the use of three-dimensional models and numerical simulations based on the finite element method has made it possible to reproduce crash tests with increasing accuracy, supporting design and verification activities and significantly reducing the need for large-scale experimental testing. In this context, explicit dynamic simulations have become an effective tool for the analysis of transient phenomena typical of impact events and for the assessment of the overall response of road restraint systems [6].

Despite the numerous contributions available in the literature, the specific role of structural spacers in determining the overall dynamic response of the barrier–vehicle system remains only partially explored. In particular, the geometry of the spacer can significantly influence deformation mechanisms, stress distribution, and the global dynamic stability of the system. In light of these considerations, the present study aims to systematically evaluate the influence of spacer geometric configuration on the global dynamic response of the barrier through a numerical analysis based on explicit dynamic simulations. A conventional solution is compared with a rhomboidal configuration, while keeping the remaining system components and impact conditions unchanged. The adopted

approach allows a direct correlation between local deformation mechanisms induced by spacer geometry and the global dynamic response of the system, providing design insights that are difficult to obtain from analyses focused exclusively on the overall performance of the barrier.

2 Background and Related Work

The scientific literature has extensively investigated the factors affecting road accident severity and the role of restraint systems in mitigating consequences for vehicle occupants. Several studies have shown that vehicle speed, impact angle, road type, traffic conditions, and infrastructure geometry significantly influence impact dynamics and the stress levels induced in the barrier [7–9,10–14].

Impacts approaching perpendicular incidence are associated with more critical collapse mechanisms and higher damage levels than oblique collisions, thus imposing more severe requirements in terms of containment and structural response control [7,10,12,13]. Moreover, probabilistic and regression-based analyses have highlighted the strong relationship between road geometry, operating conditions, and impact severity, emphasizing the need for restraint systems capable of performing under severe loading scenarios [8,9,11,14].

Within the European context, the design and verification of road safety barriers are regulated by the EN 1317 standard, which defines containment classes, test vehicles, impact configurations, and acceptance criteria for assessing the dynamic performance of restraint systems [15]. The main containment classes and corresponding energy levels are reported in Table 1, while their relationship with road environment and traffic conditions is summarized in Table 2. EN 1317 also defines standardized crash scenarios in terms of impact velocity, angle of incidence, and vehicle mass; the main parameters are reported in Table 3.

This regulatory framework provides the reference basis for barrier classification and for the definition of loading scenarios in experimental and numerical studies. In recent years, three-dimensional finite element models and explicit dynamic solvers have enabled increasingly accurate crash-test reproduction, supporting detailed analyses of deformation mechanisms, stress distributions, and transient dynamic quantities during impact [6,16]. However, these models are mainly used to assess the global barrier response, whereas the influence of individual components such as spacers on the overall dynamic behaviour has received less attention. Within the barrier–vehicle system, structural spacers play a key role in load transfer and in controlling both local and global response, yet systematic studies on the influence of spacer geometry remain limited. This motivates the need for targeted and quantitative investigations based on high-fidelity numerical models capable of capturing the transient, inertial, and contact phenomena typical of impact events.

Although EN 1317 is referenced in this work to provide the regulatory framework for the classification and testing of road restraint systems, the present study does not aim to

reproduce a standardized certification scenario. The information reported in Tables 1–3 is included only to contextualize the regulatory and application framework of road safety barriers, and not to define the exact loading conditions adopted in the experimental and numerical analyses. Instead, the simulations are formulated as a simplified comparative structural investigation, in which identical non-standard impact conditions are applied to both spacer configurations to isolate the effect of spacer geometry on the global dynamic response of the barrier.

3 Research Methodology

In this section, the dynamic response of a road safety barrier subjected to impact is analysed, with the aim of evaluating the influence of spacer geometry on the overall structural behaviour of the system.

To this end, two configurations are considered: one featuring a conventional spacer and one employing a rhomboidal spacer, while all other barrier components and loading conditions are kept unchanged. The analyses are performed through explicit dynamic numerical simulations in order to compare structural deformations, stress distributions, and the global energy response of the system as a function of the spacer configuration.

3.1 Numerical model and investigated configurations

A three-dimensional finite element model of the road safety barrier was developed, including the containment profile, posts, spacer, and connection elements. All system components and loading conditions were kept unchanged, while only the spacer geometry was modified and treated as an active design parameter to assess its influence on load transfer mechanisms and on the overall dynamic response of the barrier (Figure 1). In particular, the conventional spacer configuration is reported in Figures 1a₁ and 1a₂, in which are reported the solid model and the discretized finite element model, respectively, whereas the rhomboidal spacer equivalent models are reported in Figures 1b₁ and 1b₂, respectively. The containment profile, with a nominal thickness of 4 mm, was modelled using shell elements, whereas the posts, spacers, and connection elements were discretized using solid elements. Local mesh refinement was applied in the impact and contact regions to accurately capture deformation gradients and stress concentrations, enabling a detailed description of the plastic deformation mechanisms governing the system response. The metallic components are made of S235JR structural steel and are described using a bilinear elastoplastic material model with isotropic hardening [17]. The adopted material properties include a Young's modulus of 210 GPa, an initial yield strength of 235 MPa, a representative ultimate tensile strength of 450 MPa, a tangent modulus of 2.1 GPa, a Poisson's ratio of 0.3, and a density of 7850 kg/m³. No explicit damage, failure-strain criterion, or element erosion was introduced in the material model; therefore, the stress

and plastic-strain results are interpreted as comparative indicators rather than direct predictions of fracture. The evolution of the yield stress as a function of the equivalent plastic strain is defined by the following relationship:

$$\sigma_y = \sigma_0 + \frac{E \cdot E_h}{E - E_h} \varepsilon_p \quad (1)$$

where σ_y [MPa] is the current yield stress, σ_0 [MPa] is the initial yield stress, E [GPa] is Young's modulus, ε_p [-] is the equivalent plastic strain, and E_h [GPa] is the tangent hardening modulus. Strain-rate effects were not explicitly modelled. This choice was adopted to maintain a numerically consistent framework in line with the comparative purpose of the study, since both spacer configurations were analysed under identical impact conditions and using the same material model. Although strain-rate sensitivity is commonly considered in finite element impact simulations of steel structures through rate-

dependent constitutive formulations [18], its omission was considered acceptable for the comparative interpretation of the results. Interactions between the structural components and the impacting body are modelled using nonlinear contact formulations, while the simulations are performed using an explicit dynamic solver. The impact scenario is represented by a rigid cylindrical body with a mass of $m = 5770$ kg, adopted to reproduce a simplified frontal impact, which is assumed to represent a particularly severe loading condition. The impact is imposed by assigning an initial velocity of $v = 3.5$ m/s in the direction normal to the barrier, while the posts are constrained at their bases in order to reproduce the connection with the ground. The main time integration parameters used in the explicit analyses are summarized in Table 4. These values were manually specified to improve numerical stability during the highly transient impact phase, limiting excessive time-step growth while allowing local adaptive step reduction in the presence of severe contact evolution and localized plastic deformation.

Table 1 Containment classes of road restraint systems

Serial Number	Class Containment	Containment level [kJ]
1st	N1 minimum containment	44
2nd	N2 medium containment	82
3rd	H1 normal containment	127
4th	H2 high containment	288
5th	H3 very high containment	463
6th	H4a very high containment	572
7th	H4b very high containment	725

Table 2 Barrier containment classes by road context

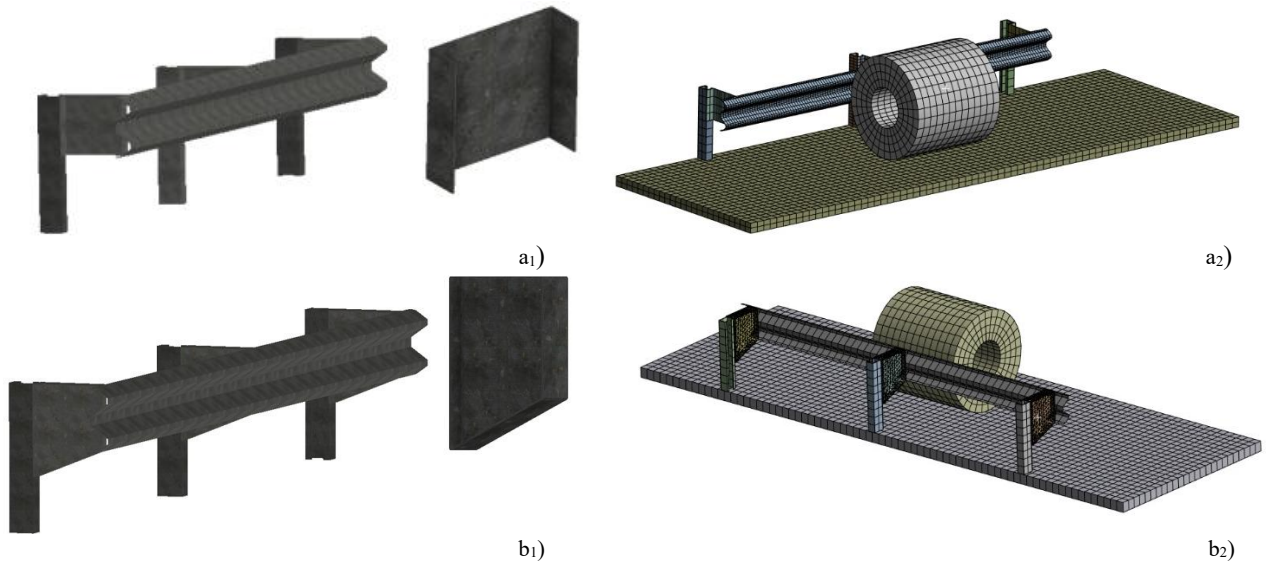
Road type	Traffic	Barriers traffic island	Barriers side edge	Barriers deck Edge	Attenuators
Highways and roads major suburban	I	H2	H1	H2	TC1 TC2
	II	H3	H2	H3	“
	III	H3-H4	H2-H3	H4	“
Suburban roads; Secondary roads and roads urban slip roads	I	H1	N2	H2	“
	II	H2	H1	H2	“
	II	H2	H2	H3	“
Urban streets of neighbourhood and local roads	I	N2	N1	H2	
	II	H1	N2	H2	
	III	H1	H1	H2	

Table 3 Classification of road restraint systems and crash attenuators

Barrier class	Speed [km/h]	Angle of Impact [degrees]	Total mass [kg]	Used vehicle
N1	80	20	1500	Car
N2	110	10	1500	Car
H1	70	15	10000	Truck
H2	70	20	13000	Truck or Bus
H3	80	20	16000	Truck
H4a	65	20	30000	Truck
H4b	65	20	38000	Tractor-trailer

Table 4 Main time integration settings adopted in the explicit dynamic simulations

Parameter	Value
End time	1.0×10^{-1} s
Maximum admissible energy error	0.1
Initial time step	5.0×10^{-7} s
Minimum time step	1.0×10^{-8} s
Maximum time step	2.0×10^{-6} s
Time step safety factor	0.9

**Fig. 1** Investigated spacer configurations: (a) conventional spacer: (a₁) solid model; (a₂) discretized model; (b) rhomboidal spacer: (b₁) solid model; (b₂) discretized model

The main contact interfaces in the numerical model were defined between the inner surface of the barrier and the outer surface of the spacer, as well as between the opposite end of the spacer and the contact surface of the post. These interfaces were modelled using a nonlinear frictional contact formulation, assuming a constant Coulomb friction coefficient of $\mu = 0.20$, which was kept unchanged in all simulations to ensure numerical consistency and provide a consistent basis for the comparative assessment among the analysed configurations. This modelling choice was adopted to represent the contact interaction and load transfer between adjacent components within a simplified and computationally efficient numerical framework, consistent with numerical approaches commonly adopted in the literature.

3.2 Manufacturing Analysis and Process Evaluation

A preliminary Design for Manufacturing (DfM) assessment of the proposed rhomboidal spacer was carried out to evaluate the compatibility of its geometry with an industrial manufacturing process based on flat-sheet blank cutting followed by sequential cold-bending operations. The configuration was defined assuming a nominal sheet thickness of $t=4$ mm, two lower bending angles, α_1 and α_2 , equal to 111° and 68° , respectively, and a bend radius $R = 6$ mm along the transition regions between the straight portions of the profile (Fig. 2). The main manufacturability constraints considered in defining the component geometry are summarized in Table 5. This choice helps limit excessive local concentrations of plastic strain and ensures a smoother geometric transition along the component profile. A further

aspect concerns compatibility with the flat-pattern development of the blank, which can be assessed in simplified form using the conventional bend allowance relationship:

$$BA = \theta(R + Kt) \quad (2)$$

where θ is the effective bending angle, expressed in radians, R is the inner bend radius, t is the sheet thickness, and K is the neutral-axis position factor. Although no dedicated forming-process simulation was performed, this formulation provides a simplified assessment of the compatibility of the proposed geometry with manufacturing from a flat blank through standard sequential bending operations. Furthermore, the adopted geometric configuration was defined by avoiding excessively abrupt transitions and by limiting the number of geometric control parameters, with the aim of reducing sensitivity to springback phenomena and the risk of undesirable strain localization in the bending regions. In this respect, the rhomboidal spacer can be regarded as a preliminary DfM-oriented solution in which structural requirements are balanced with simplified manufacturability constraints consistent with conventional industrial sheet-metal processing practices [19]. The proposed rhomboidal spacer is also compatible with a conventional manufacturing process in terms of cost drivers, scalability, process repeatability, and quality control. In particular, the main cost drivers are associated with material consumption, cutting and bending operations, and final dimensional inspections. Manufacturing from a flat blank through sequential cold-bending operations also makes the proposed solution suitable for both batch and serial production. At the same time, the limited number of

geometric control parameters and the use of a constant bend radius promote process repeatability, while quality control can be based on standard dimensional inspections of the final component profile. To account for typical manufacturing variability, a thickness sensitivity analysis of $\pm 5\%$ with respect to the nominal value was performed. The corresponding effects on the main structural response indicators are discussed in Section 4.2 and summarized in Fig. 10.

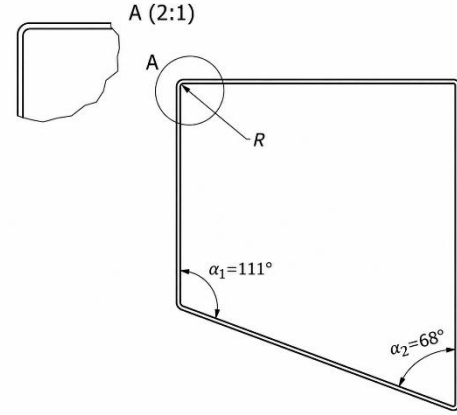


Fig. 2 Orthographic side view of the rhomboidal spacer with bending angles α_1 , α_2 and bend radius R

Table 5 Main design-for-manufacturing parameters of the proposed rhomboidal spacer

Parameter	Description	Manufacturing relevance
Sheet thickness	$t=4\text{mm}$	Compatible with conventional sheet-metal manufacturing processes
Bend radius	$R=6\text{ mm (constant)}$	Ratio $R/t = 1.5$, consistent with standard bending practice and useful for limiting local strain concentration
Main geometric angle	$\alpha_1=111^\circ$	Governs the lower-left profile configuration
Main geometric angle	$\alpha_2=68^\circ$	Governs the lower-right profile configuration
Flat-pattern compatibility	Simplified verification through bend allowance $BA = \theta(R + Kt)$	Confirms manufacturability from a flat blank through sequential bending operations
Sensitivity to forming defects	Preliminary qualitative assessment	Geometry defined to reduce the risk of springback and excessive strain localization in bending regions

3.2.1 Preliminary Production Efficiency and Flexibility Assessment

The comparison between the conventional C-shaped spacer and the proposed rhomboidal configuration highlights relevant differences in terms of manufacturing sequence, expected cycle time, and production flexibility. The

conventional spacer can be manufactured using two main bending operations, whereas the rhomboidal solution consists of a sheet-metal blank subjected to three main bending operations and completed by the addition of a separate lateral plate. Consequently, the rhomboidal configuration involves a slightly more complex manufacturing sequence and an expected cycle time that is moderately higher than that of the conventional solution. A

simplified cycle-time model was used to compare the two bending sequences. In press-brake processing, the total time depends not only on the bending operation itself, but also on part loading, positioning, and repositioning between consecutive bends, which are relevant aspects of sheet-metal bending process planning [20]. A representative industrial press-brake example reports characteristic times of about 5 s for part loading and positioning, 5 s for each bending operation, and 5 s for repositioning between successive bends [21]. The bending-stage cycle time was calculated as:

$$T_c = t_L + n_b T_b + (n_b - 1) t_r \quad (3)$$

where t_L is the initial loading and positioning time, n_b is the number of bending operations, T_b is the reference time for each bending operation, and t_r is the repositioning time between consecutive bends. The resulting bending-stage cycle times are approximately 20 s for the conventional spacer and 30 s for the rhomboidal spacer, corresponding to an increase of about 50%. These values result from applying the calculation model to the reference times adopted for loading, bending, and repositioning operations. However, under the assumed comparable bending conditions, no additional tool changes were considered necessary, since geometric variations of the profile can be achieved mainly by adjusting the punch stroke and the operating sequence. In particular, the proposed geometry can be adapted by varying the bending angles without requiring additional tooling

changes, thereby increasing process flexibility. In this respect, the proposed configuration is not intended to reduce the overall manufacturing complexity, but rather to provide greater geometric flexibility while maintaining a production approach based on conventional sheet-metal cutting, bending, and assembly operations. The main aspects related to production efficiency and process flexibility of the two configurations are qualitatively summarized in Table 6. The manufacturing workflow associated with the proposed rhomboidal spacer is schematically illustrated in Fig. 3.

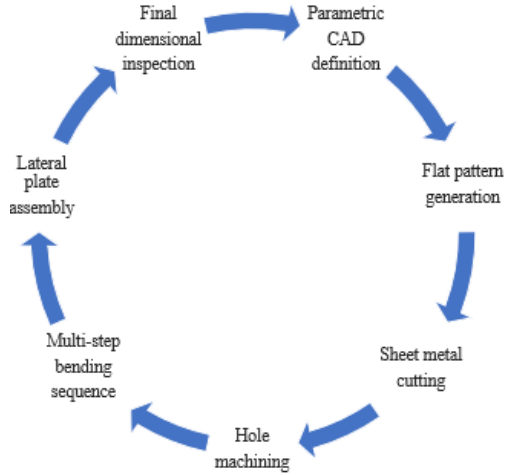


Fig. 3 Simplified manufacturing workflow adopted for the proposed rhomboidal spacer

Table 6 Principal production-efficiency and manufacturing-flexibility parameters of the investigated spacer configurations

Parameter	Conventional C-shaped spacer	Proposed rhomboidal spacer
Main bending operations, n_b	2	3
Initial loading and positioning time	≈ 5	≈ 5
Reference bending time, T_b [s/ben]	≈ 5	≈ 5
Intermediate repositioning operations	1	2
Reference repositioning time, t_r [s/operation]	≈ 5	≈ 5
Estimated bending-stage cycle time, T_c [s]	≈ 20	≈ 30
Additional assembly element	None	Lateral plate
Additional tool changes	None	None
Production flexibility	Limited	Higher

4 Results and Discussion

4.1 Model Validation

The numerical model was validated using experimental acceleration data obtained from controlled impact tests performed on a full-scale guardrail system. The experimental setup involved the interaction between a metallic cylindrical body and the barrier in a frontal impact configuration, representative of the most severe loading conditions considered in the study. Figure 4 summarizes the experimental setup, including the metal coil used as the impacting body, the guardrail deformation after impact, and the layout of the accelerometer positions. The system was instrumented with piezoelectric accelerometers at two significant locations: Point 2 on the barrier profile and Point 1 at the central post. Figures 5 and 6 therefore show the direct

comparison between experimental and numerical acceleration time histories at Point 2 and Point 1, respectively. The analysis was carried out over a common time window of $t = 0.1$ s, representative of the initial and most significant stage of the impact event. Within this interval, the main inertial and contact phenomena, as well as the most relevant acceleration peaks, are concentrated, making this time span the most representative for comparative validation purposes. The comparison shows an overall satisfactory agreement between the experimental and numerical responses. Although unavoidable local discrepancies are present, a substantial correspondence can be observed in terms of the overall response trend, impulse duration, and magnitude of the main acceleration peaks. These results confirm that the numerical model is suitable for the comparative assessment between the conventional spacer and the rhomboidal spacer configurations. The present validation is intentionally limited to the comparison

of acceleration time histories, as these represent the only experimental quantity directly available for comparison with the numerical model. Therefore, it supports the capability of the model to reproduce the global dynamic response of the barrier during impact, but does not provide direct verification of other quantities subsequently analysed in the study, such as local deformations, stress states, or energy absorption, which are therefore interpreted primarily as comparative numerical indicators rather than as fully validated absolute results.

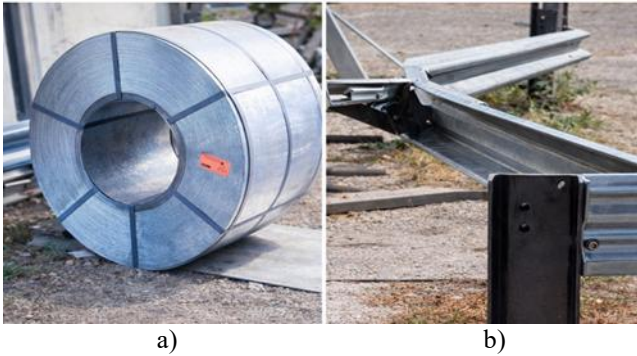


Fig. 4 Experimental setup: (a) metallic coil at the impact stage; (b) guardrail deformation after impact; (c) accelerometer positions on the barrier profile (Point 2) and central post (Point 1).

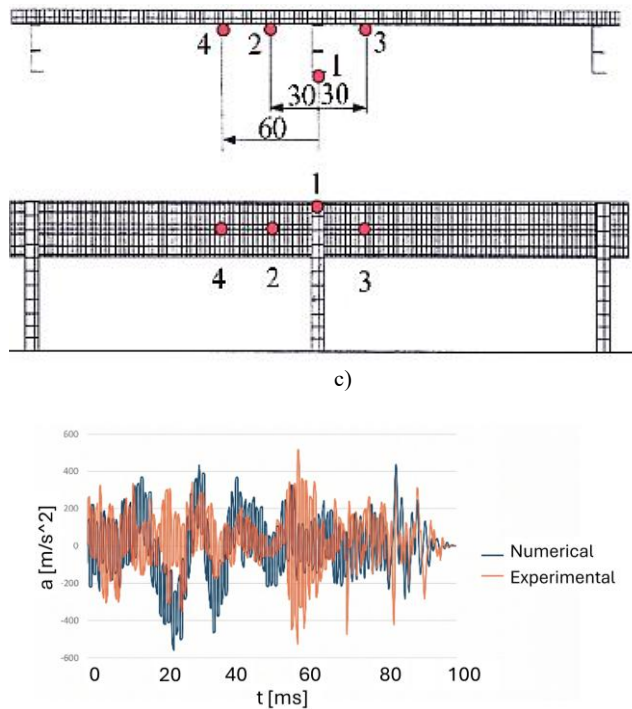


Fig. 5 Comparison between experimental and numerical acceleration at Point 2

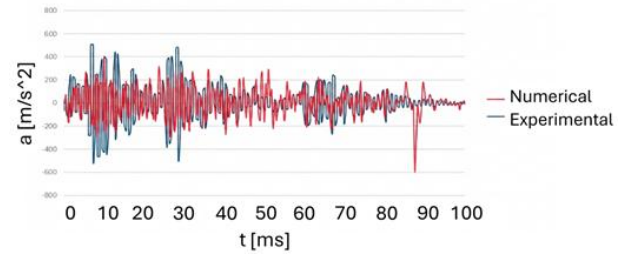


Fig. 6 Comparison between experimental and numerical acceleration time histories at Point 1

4.2 Structural response

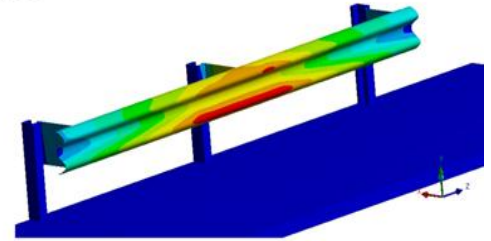
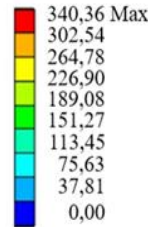
The structural response of the barrier is analysed in terms of global displacements, equivalent stress distribution, and plastic deformation, in order to evaluate the influence of spacer geometry on the overall dynamic behaviour of the system. The configurations featuring conventional and rhomboidal spacers are compared while keeping the impact conditions and numerical model parameters unchanged. The total displacement maps highlight differences in the global structural response (Figure 7).

A: Explicit Dynamics

Total Deformation

Type: Total Deformation

Unit: mm



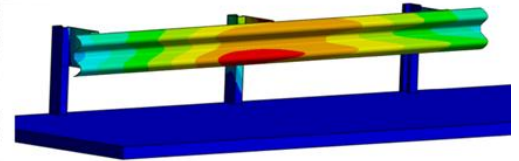
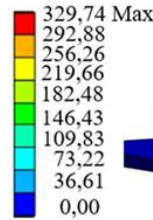
a)

A: Explicit Dynamics

Total Deformation

Type: Total Deformation

Unit: mm



b)

Fig. 7 Comparison of the numerical displacement fields obtained for (a) the conventional spacer configuration and (b) the rhomboidal spacer configuration

The total displacement maps reveal limited but consistent differences in the global structural response (Figure 7). In particular, the configuration with the rhomboidal spacer exhibits a reduction in the maximum displacement magnitude, accompanied by a more uniform distribution of

the deformation fields compared to the solution with the conventional spacer. From a quantitative standpoint, the reduction in the maximum barrier deflection indicates improved control of the system's structural kinematics. This behaviour limits the propagation of deformations along the longitudinal axis of the barrier, contributing to a more controlled global response under impulsive loading conditions. The von Mises equivalent stress distributions for the two configurations are shown in Figure 8. In both configurations, the maximum equivalent stresses locally exceed the initial yield strength, without indicating a loss of comparative structural integrity within the adopted constitutive model. The regions of maximum stress are mainly localized near the connection areas between the barrier profile and the supporting elements, in agreement with the kinematics of the impact event.

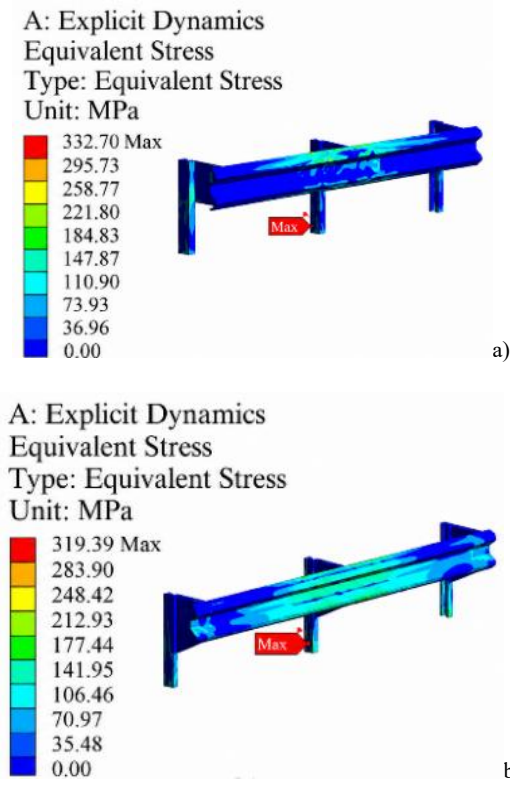


Fig. 8 Comparison of the numerical stress distribution: (a) conventional spacer configuration and (b) rhomboidal spacer configuration

The comparison of the equivalent plastic strain maps, shown in Figure 9, indicates that for both configurations the maximum plasticization is concentrated in the lower region of the central post, consistently with the overall deformation mechanism of the structure. The equivalent plastic strain maps show that the deformation mechanism is predominantly governed by the central post, while the lateral posts exhibit only limited plastic involvement. However, the configuration with the rhomboidal spacer exhibits a reduction in plastic strain compared to the conventional solution, together with a lower concentration of plastic

deformation in the lower region of the post. This result suggests a more favourable distribution of stresses during the impact event.

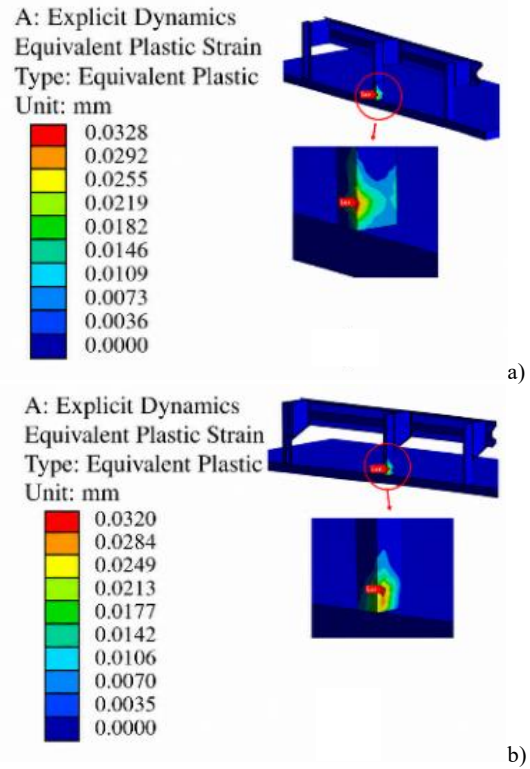


Fig. 9 Equivalent plastic strain distribution for the two spacer configurations: (a) conventional spacer; (b) rhomboidal spacer

A sensitivity analysis was performed by varying the mesh size (20, 15, and 10 mm), sheet thickness (3.8, 4.0, and 4.2 mm), and yield strength (223.25, 235, and 246.75 MPa). Thickness and yield-strength variations were evaluated using the 10 mm fine mesh, varying one parameter at a time. The resulting changes in total deformation, equivalent stress, and equivalent plastic strain are summarized in Fig. 10. The global behaviour of the system was also evaluated by means of the Acceleration Severity Index (ASI). Since the adopted impact scenario is represented by an equivalent rigid cylindrical mass rather than a real vehicle, the ASI was used exclusively as a comparative and non-certification indicator. The conventional formulation reported in Eq. (4) was applied to the three orthogonal acceleration components of the equivalent cylindrical impactor. The acceleration components a_x , a_y , and a_z were obtained from the numerical response of the equivalent rigid cylindrical impactor and evaluated at its centre of mass, assumed as the representative point of its global motion. For each analysed impact condition, the final ASI value was taken as the maximum value reached during the entire impact event. It should be emphasized that, due to the simplified representation of the impactor by means of an equivalent cylindrical mass, the obtained ASI values are not intended to reproduce certified occupant severity levels, but only to provide a consistent and homogeneous comparison among the different analysed

configurations. Table 7. Maximum ASI values and corresponding maximum barrier deflections for the rhomboidal-spacer configuration at the investigated impact angles.

$$ASI(t) = \sqrt{\left[\left(\frac{a_x}{12g}\right)^2 + \left(\frac{a_y}{9g}\right)^2 + \left(\frac{a_z}{10g}\right)^2\right]} \quad (4)$$

where a_x , a_y , and a_z represent the longitudinal, lateral, and vertical acceleration components, respectively, while g is the gravitational acceleration.

Table 7 Comparative ASI values and maximum barrier deflections for the considered impact angles

Angle of Impact [degrees]	ASI Index [-]	Max Deflection [mm]
20	≈ 0.72	245
45	≈ 0.81	275
90	≈ 0.97	329.74

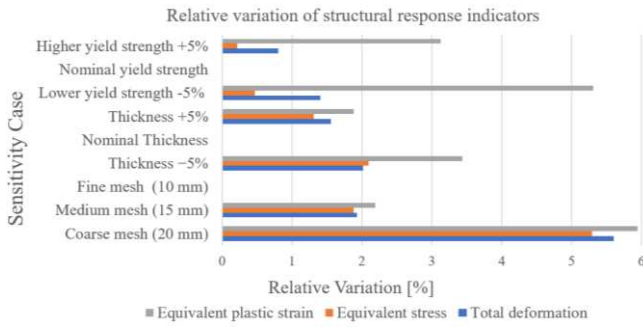


Fig. 10 Relative variation of the main structural response indicators with respect to the nominal configuration adopting the 10 mm fine mesh

4.3 Energy conservation and numerical stability

The global energy balance was analysed in order to assess the numerical stability of the explicit dynamic simulations and to compare the behaviour of the two investigated spacer configurations. Figure 11 shows the time histories of the total energy, reference energy, and external work, as well as the global energy error. For both configurations, the total energy is essentially conserved throughout the entire simulation, with limited variations mainly concentrated during the impact phase. The energy error remains small relative to the reference energy, indicating good numerical stability of the adopted model.

In order to provide a quantitative assessment, the energy error was normalized with respect to the reference energy, defining the following ratio:

$$E_{norm} = \frac{E_{error}}{E_{Ref}} \quad (5)$$

The simulations were evaluated over a common time window of 0.1 s, selected to consistently represent the early impact-dominated stage and enable a homogeneous comparison between the two geometries. Although the energy transfer process is not yet fully completed at the end of the selected interval, the main response trends and the

differences between the two configurations are already clearly visible within 0.1 s. In both cases, the total energy remains close to the reference energy, although a slight downward drift is observed in the final part of the analysed interval. This behaviour can be attributed to a limited numerical deviation, which is typical of explicit simulations involving nonlinear contact and strong transient effects, but it remains very small relative to the reference energy and does not compromise the overall numerical stability of the model. The energy summary plots further show a progressive decrease in kinetic energy and a corresponding increase in internal energy, consistent with the transfer of impact energy into structural deformation. The hourglass energy remains very low compared to the internal energy, while the contact energy stays limited and regular. Overall, the rhomboidal spacer exhibits a slightly more regular numerical response than the conventional configuration. Although no universally defined threshold exists for energy conservation in explicit dynamic simulations, deviations below about 10% can be considered acceptable in complex impact analyses involving nonlinear contact and plastic deformation, consistently with the default energy-error reference level adopted in ANSYS Explicit Dynamics [22]. In the present study, the observed energy deviation remained below this level, confirming the numerical stability of the model and the comparative reliability of the obtained results.

4.4 Overall performance comparison

The overall comparison between the two spacer configurations allows the effects of spacer geometry on the global dynamic response of the barrier to be summarized. The main performance indicators extracted from the numerical analyses, namely maximum displacements, von Mises equivalent stresses, and equivalent plastic strain, are reported in Table 8 for both configurations considered.

The results show that the configuration with the rhomboidal spacer is associated with slightly lower values of the considered indicators compared to the conventional solution. In particular, a limited reduction in the maximum barrier displacement, peak equivalent stresses, and equivalent plastic strain is observed. Although these differences are of limited magnitude, they are consistent with the qualitative observations emerging from the analysis of deformation, stress, and plasticization fields discussed in the previous sections.

Overall, the quantitative comparison confirms that variations in spacer geometry influence the global structural response of the barrier, providing useful insights for the comparative evaluation of alternative design solutions without introducing changes to the loading conditions or to the overall system configuration. From an integrated structural-manufacturing perspective, the reductions in maximum displacement (3.1%), von Mises stress (4.0%), and equivalent plastic strain (2.4%) obtained with the rhomboidal configuration are accompanied by one additional bending operation and an increase in the estimated bending-stage cycle time from approximately 20 s to 30 s.

5 Conclusions

In this work, the influence of structural spacer geometry on the dynamic response of a guardrail system was investigated through explicit dynamic numerical simulations supported by experimental acceleration data. Two spacer configurations, namely a conventional solution and a rhomboidal geometry, were compared under identical impact and modelling conditions in order to isolate the effect of spacer topology on the global structural response.

The results showed that the rhomboidal configuration provides limited but consistent improvements in the main structural response indicators. Compared with the conventional spacer, the maximum barrier displacement decreased from 340.36 mm to 329.74 mm, corresponding to a reduction of approximately 3.1%, while the maximum von Mises equivalent stress decreased from 332.70 MPa to 319.39 MPa, with a reduction of about 4%. The maximum equivalent plastic strain also decreased from 0.0328 to 0.0320, corresponding to a reduction of approximately 2.4%. These results indicate that spacer geometry influences the deformation mechanism and stress distribution of the barrier, although the observed improvements remain moderate.

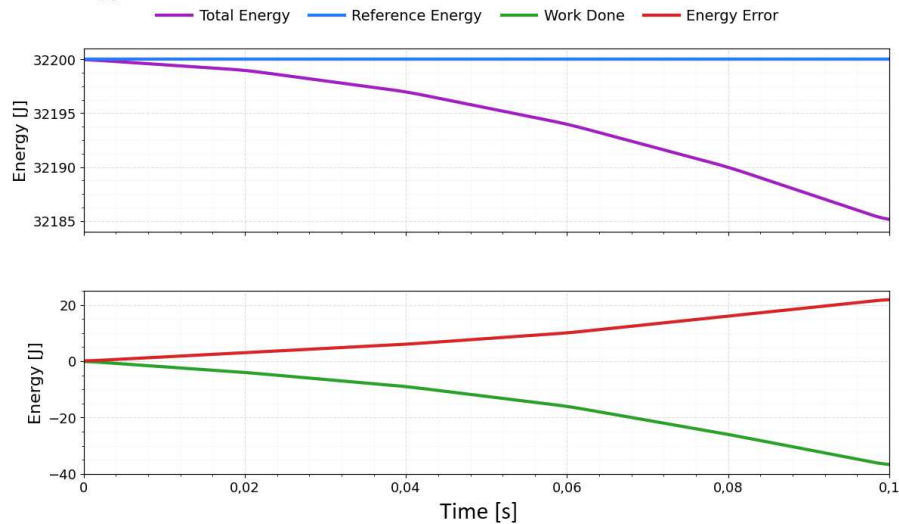
The energy-balance analysis confirmed good numerical stability for both configurations, with limited energy deviations during the analysed impact interval, supporting

the comparative reliability of the simulations. The sensitivity analysis further showed that the principal structural response indicators remain reasonably consistent under variations in mesh size, sheet thickness, and yield strength, strengthening the robustness of the comparative assessment.

From a manufacturing perspective, the proposed rhomboidal spacer remains compatible with conventional sheet-metal cutting and cold-bending processes. The configuration requires three main bending operations instead of two and an additional lateral plate. Based on the adopted press-brake reference times, the estimated bending-stage cycle time increases from approximately 20 s for the conventional spacer to 30 s for the rhomboidal configuration. The proposed geometry therefore involves a higher processing time while providing greater geometric flexibility without requiring additional tooling changes.

The findings demonstrate that spacer geometry can be treated as an effective design variable within an integrated simulation-driven and manufacturing-oriented framework for road restraint systems. The proposed approach provides a basis for the comparative evaluation of alternative spacer geometries by jointly considering structural response and manufacturing feasibility. Future developments will focus on additional impact scenarios and incidence angles, further experimental validation, and more detailed manufacturing-process assessments to support the development of more robust and industrially applicable guardrail components.

Energy Conservation



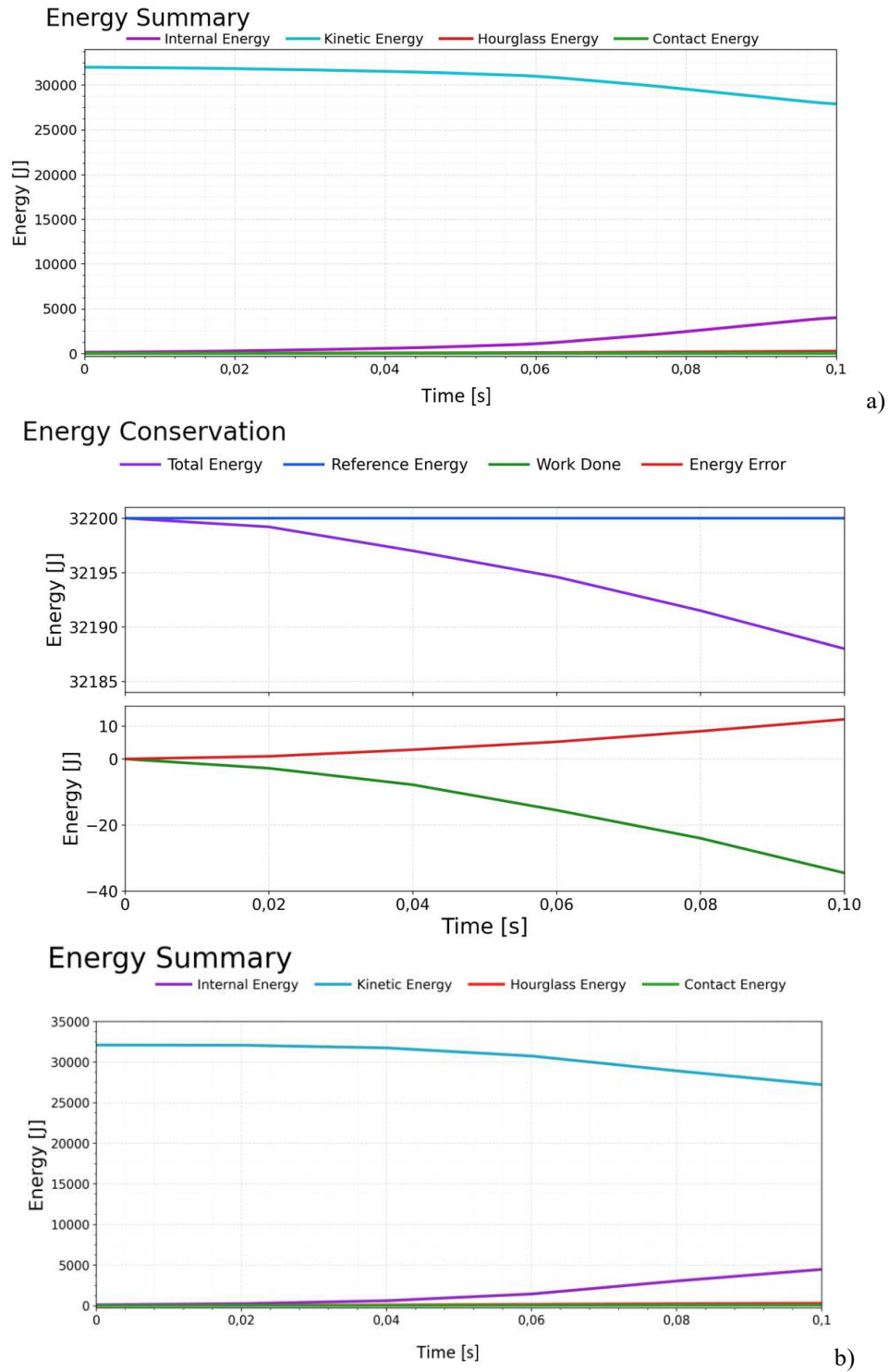


Fig. 11 Energy conservation and energy summary plots for the (a) conventional spacer and (b) rhomboidal spacer

Table 8 Comparison of global performance indicators for the conventional and rhomboidal spacer configurations

Performance indicator	Conventional spacer	Rhomboidal spacer	Relative Difference [%]
Max displacement [mm]	340.36	329.74	3.1 %
Max Von Mises stress [MPa]	332.70	319.39	4%
Equivalent Plastic Strain	0.0328	0.0320	2.4 %

Statements & Declarations

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Competing Interests

The authors declare that they have no financial or non-financial interests that are directly or indirectly related to the work submitted for publication.

Availability of Data and Materials

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Ethics Approval

Not applicable.

Consent to Participate

Not applicable.

Consent for Publication

Not applicable.

Author Contributions

M.C. contributed to the conceptualization of the study, methodology development, supervision, and critical revision of the manuscript. G.L. and S.M. contributed to the development of the numerical model, the explicit dynamic simulations, and the processing and analysis of the numerical results. G.B. and G.D.M. contributed to the preparation of the original draft and the revision of the manuscript. All authors contributed to the discussion and interpretation of the results, reviewed the manuscript, and read and approved the final version.

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