Railway-vehicles crashes: A study on energy absorbers in offset conditions

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Recent growth in railway traffic has resulted in several accidents and casualities that in turn have jeopardized one of the safest means of transport to date. Energy absorbers, the devices designed to absorb impact energy during a collision to protect passengers and preserve cabin integrity, play a critical role in mitigating collision impacts by dissipating kinetic energy and safeguarding structural integrity and, therefore, passengers. However, increasingly, public and regulatory authorities are requesting that their reliability also be guaranteed under off design conditions.

One of these off-design conditions is the offset or eccentric impact, where vehicles collide without perfect frontal alignment, introducing a degree of eccentricity.

Nevertheless, despite the growing importance of eccentric impact scenarios for railway vehicle homologation, the open scientific literature offers limited studies on energy absorbers in this off-design condition. Energy absorbers, such as crash buffers and crumple zones, were first introduced in railway vehicles in the mid-20th century as part of efforts to improve crashworthiness.

Early developments in crash energy management (CEM) systems began in the 1960s and 1970s, particularly in high-speed rail applications and heavy freight railcars. The mandatory implementation of energy absorbers in railway vehicles has varied by country and region. In Europe, crashworthiness standards were significantly reinforced with the introduction of EN 15227 in 2008, last updated in 2024 [1], which mandated energy absorption structures and eccentric scenarios.

This study provides the basis for analysing the effects of offset impacts in the railway sector and derives key principles for the design of energy-absorbing structures in metal alloys, such as steel or aluminum typically used in these applications.

A numerical simulation was performed on various types of tubular absorbers (hereafter referred to as "tubes"), including simple tubes (TWS, thin-walled structures), conical tubes (TWDTS, thin-walled double tapered structures), tubes with internal longitudinal septa (TWMCS-LS, thin-walled multi-cell structures – longitudinal septa), and tubes with an additional inner tube (TWMCS-BT, thin-walled multi-cell structures – bi-tubular tubes), see Fig.1.

All these configurations operate on the principle of energy dissipation through controlled crushing (or folding): when subjected to axial compressive loading, the tube forms plastic hinges that progressively create folds. This process allows irreversible energy dissipation through plastic deformation of the material. The correct and controlled formation of these folds is essential to ensuring efficient energy absorption during a collision.

The energy absorber models investigated in this study were developed using finite element (FE) analysis and evaluated through 240 simulations in which several geometric parameters were varied, including tube and septum thickness, external and internal dimensions, number of septa, conicity (ratio between the front and rear sections), and cross-sectional shapes.

The simulations were conducted with the explicit solver LS-DYNA R12.2.1, on HPC cluster using 128 CPUs and 185GB memory. All geometries adhere to a maximum cross-sectional dimension (or maximum footprint) constraint of 300 mm × 300 mm and a tube length of 400 mm, in line with typical applications for Metro C-II category vehicles (Standard EN 15227). All analyses were performed using a 10 mm mesh size, employing fully integrated shell elements for the plates and solid elements for the anticlimbers, in turn positioned with a vertical offset of 40 mm, in accordance with the eccentricity condition defined in the standard [1].

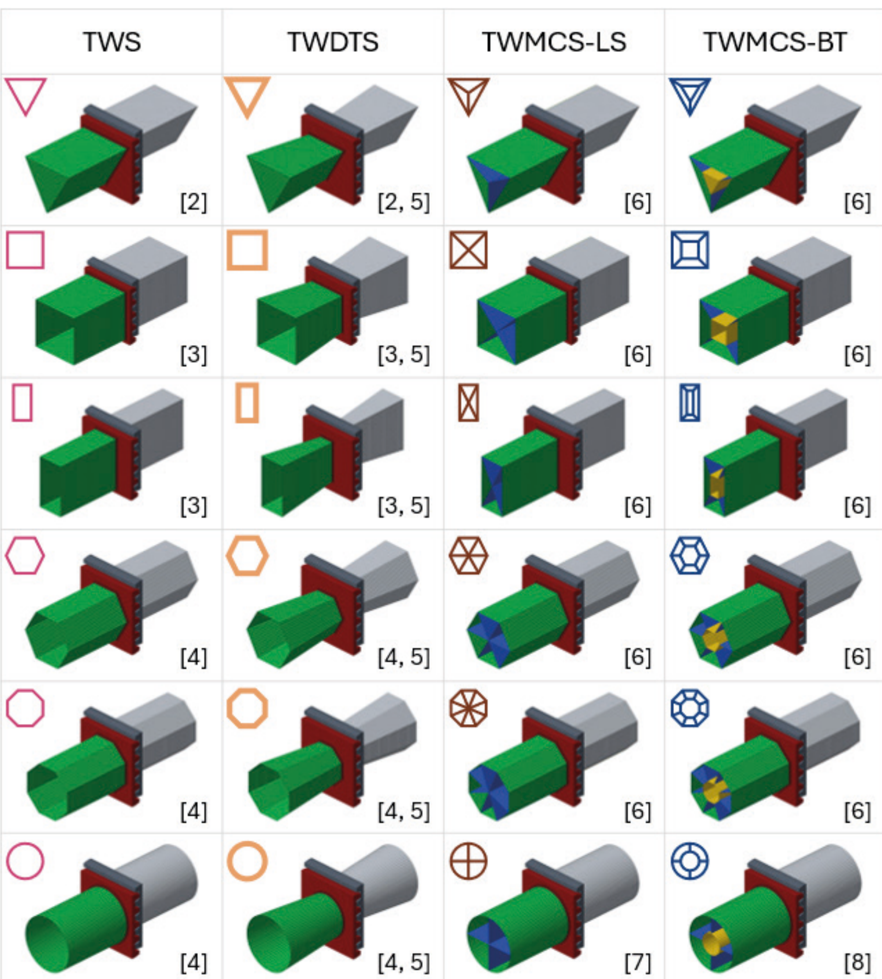

Fig.1. Type, shape, and references [#] for all the analytical formulations in this study.

Each configuration under offset impact conditions was evaluated using the energy ratio indicator R, which expresses the ratio between 1) the energy absorbed during an offset impact, as determined by numerical simulations, and 2) the energy that the absorber would dissipate under ideal, purely axial impact conditions.

The latter was calculated using theoretical analytical formulations available in the literature (Fig.1) and implemented in MATLAB to account for all parameterized variations in the offset scenario.

These analytical formulations enable the estimation of the energy absorbed during the plastic formation of folds, under a perfectly axial and stationary crushing mechanism. This approach ensures that for each offset simulation, the corresponding energy value under purely axial conditions is available, allowing an accurate determination of R among all the considered geometric variations.

The results indicate that increasing the cross-sectional dimensions leads to a higher energy ratio R. Conversely, variations in thickness do not have a comparable effect. Although thickness is a critical parameter for the total amount of energy dissipated in both axial and eccentric impact conditions, its variation

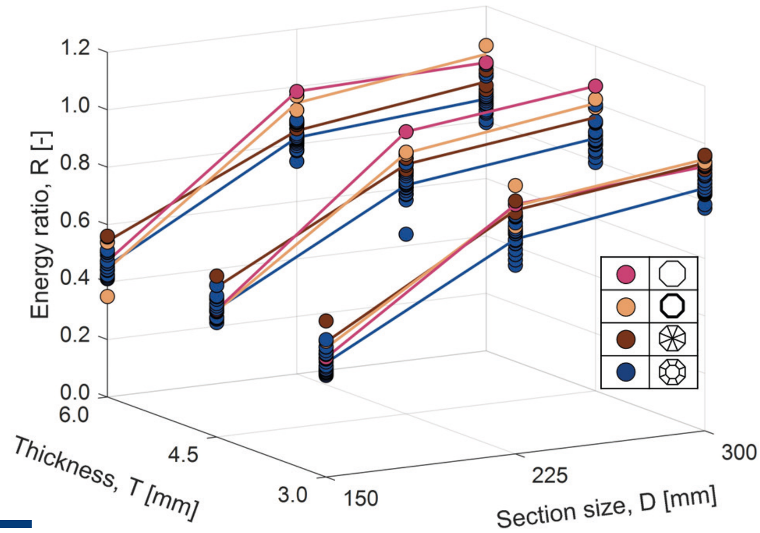

Fig.2. Influence of section size and thickness on energy ratio.

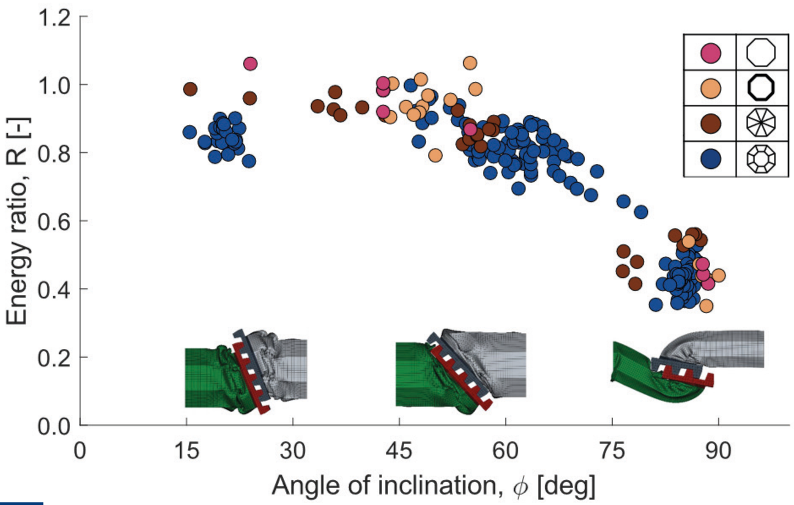

Fig.3. Relationship between angle of inclination and energy ratio.

does not improve the energy ratio R (Fig.2). Similarly, no specific absorber type outperformed the others in terms of the energy ratio R.

Further analysis of the absorption phenomenon revealed the existence of a minimum cross-sectional dimension below which buckling instability occurs, leading to significant rotations between the two absorbers and a loss of energy dissipation efficiency.

However, by correlating the energy ratio R with the angle of inclination ϕ between the absorbers (Fig.3), it was observed that the inclination — outside the instability region associated with buckling instability — does not serve as an effective indicator of the absorber dissipation capacity. In this region, indeed, the energy ratio R remains almost constant even for large angles of inclination between the two absorbers, leading to a suitable energy dissipation albeit the incompleteness of folds.

In addition, the use of cross-sectional shapes with acute or right-angled vertices (Table 1), such as triangles, squares, and rectangles, has been shown to limit the absorber inclination ϕ and increase the number of complete folds — a key parameter for the energy absorption efficiency of these devices (Fig.4). A section with acute or right-angled vertices produces higher resistances near these points, in accordance with analytical formulations of absorber dissipation.

These higher resistances contribute to more controlled crushing, facilitating the formation of complete folds and allowing a deformation mechanism like that observed under purely axial impact conditions.

In conclusion, this study highlights the crucial role of the cross-sectional dimensions of the energy absorbers: increasing this parameter improves the energy ratio R. The buckling instability only occurs below a certain minimum cross-sectional dimension, leading to significant rotations between the two absorbers (over about 70 degrees) and a notable loss of energy dissipation efficiency.

However, it is worth noting that a certain inclination between two absorbers does not necessarily result in significantly lower energy absorption compared to axial conditions even in presence of incomplete folds — outside the buckling instability region.

Besides, the absorber type (TWS, TWDTS, TWMCS-LS, and TWMCS-BT) and wall thickness have no significant effect on the energy ratio R. Conversely, cross-sectional shapes with acute or right-angled vertices effectively minimize the angle of inclination ϕ between absorbers for all the typologies, ensuring a crushing mechanism equivalent to purely axial scenarios with the formation of complete and controlled folds.

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TWS			TWDTS			TWMCS-LS			TWMCS-BT		
Shape	R (-)	ϕ (deg)	Shape	R (-)	ϕ (deg)	Shape	R (-)	ϕ (deg)	Shape	R (-)	ϕ (deg)
	1.01	7.9		1.04	5.7		0.94	9.2		0.98	7.9
	0.96	4.7		0.95	3.5		1.02	5.2		0.99	5.8
	1.03	2.4		0.95	4.9		0.96	2.2		0.96	5.1
	0.95	25.8		0.96	43.1		1.04	9.7		0.92	50.6
	0.97	41.8		0.96	49.1		0.92	38.4		0.89	60.1
	0.95	52.1		0.95	48.7		0.89	52.5		0.85	63.4

Table 1. Relationship between shapes of different typologies, inclination angle and energy ratio.

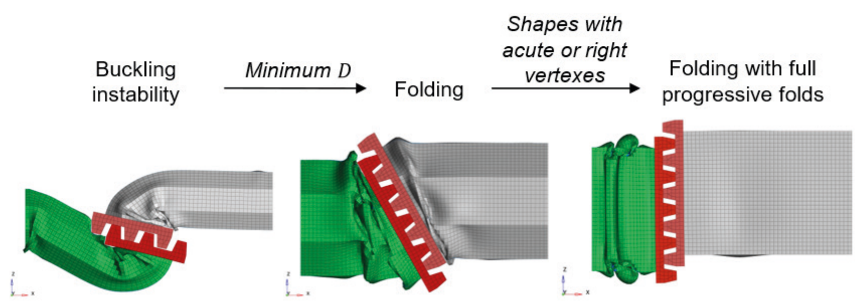

Fig.4. Summary of the main conclusions.

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