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ENHANCING ROAD SAFETY WITH THE INFRASTRUCTURE-ADAPTABLE NDBA 2.0 CONCRETE MEDIAN BARRIER: AN ITALIAN EXPERIENCE

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Abstract:

Road safety is a crucial global concern because of the high number of fatalities and injuries resulting from road crashes each year. Median crossover collisions are among the most dangerous crashes that happen on highways, frequently leading to serious or fatal injuries. The main approach to decreasing the occurrence of these types of crashes is the installation of median barriers. When the need for such installations arises, road agencies must choose from various options, including concrete barriers, cable barriers, or metal-beam guardrails. This paper is dedicated to the New Dynamic Barrier for Highways (NDBA 2.0), an innovative technology for median barriers developed by the Italian National Road Agency (ANAS), emphasizing its pivotal role in enhancing road safety. It incorporates high-tensile steel and advanced composites, offering robust protection while maintaining a lightweight profile. What distinguishes the NDBA 2.0 is its dynamic nature, featuring an intelligent system that seamlessly adapts to the road infrastructure. Its modular construction, with sections of only 200 cm, allows for easy installation and ensures compatibility across successive road segments. This adaptability reduces construction time while maintaining the highest standards of performance. From a road safety perspective, the NDBA 2.0 offers substantial advantages. Its design contributes to minimizing crash-related costs by reducing the severity of crashes, particularly in the transition zones. The barrier's design allows it to adapt to varying road conditions and traffic volumes, effectively addressing common installation challenges on existing roadways as well. Its ability to be directly supported on the road surface wear layer eliminates the need for costly foundation structures, facilitating quick installation and reducing maintenance expenses. The NDBA 2.0 barrier was designed to eliminate the need for future simulations in the design and verification of transitions between different barriers. For this reason, the NDBA 2.0 barrier has been tested in real-world conditions in class H4 and, consequently, is equipped with CE marking. This study offers a comprehensive analysis of the NDBA 2.0 barrier, whose implementation may provide significant benefits for road safety. Continued research, collaboration, and widespread adoption of the NDBA 2.0 barrier can further enhance road safety on a global scale.

Keywords: *concrete safety barrier, road safety, full-scale crash test, road transport, road engineering*

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1. Introduction

Road restraint systems are crucial for transport infrastructure, designed to redirect or absorb vehicle impact, reducing collision severity and enhancing overall road user safety (Lie and Tingvall, 2024) (Zou and Tarko, 2016). The theoretical and experimental study of road restraint systems began in the 1930s in the United States, spreading to highly motorized countries to define types, materials, properties, qualities, locations, and installation methods (Sklet, 2006). The construction features and the materials chosen give these devices high strength, durability, and energy-absorbing properties; the choice of materials depends on factors such as the type of road, traffic volume, speed, and safety requirements (Liu, 2020). Commonly used on motorways, highways, and bridges, their purpose is to prevent vehicles from veering off the roadway and to minimize the harmful effects on passengers in the event of a collision (Bareiss et al., 2023) (Zou et al., 2014). Additionally, these structures can become obstacles. Therefore, it is imperative to skillfully install them to prevent vehicles from surmounting the barriers and to protect everything beyond them (Budzynski et al, 2019).

Depending on the characteristics of the roadway environment, road restraint systems are categorized into safety barriers, median barriers, crash cushions, terminals installed at the beginning or end of a safety barrier, access closures, and protections for motorcyclists (Sklet, 2006). The selection of the barrier type also depends on specific technical requirements (Tahmasseby et al., 2021). On European roads, barriers adhere to Standard EN 1317-1 (2010), which sets out universal testing and certification protocols for road restraint systems. This standard doesn't prescribe barriers for specific situations but instead mandates tests that classify products into performance classes. It also stipulates safety levels and spatial requirements, ensuring optimal road safety across diverse scenarios. EN 1317 comprises several parts, each addressing distinct aspects and classifications of specific products within the realm of road safety (EN 1317-1 and EN 1317-2, 2010).

The regulatory framework in Italy concerning road restraint systems is intricate and multifaceted due to the issuance of numerous legislative decrees and ministerial circulars over the years. The initial technical regulation governing the design, validation, and installation of safety barriers dates back to 1992, focusing on performance aspects in addressing safety barriers (Italian Ministry of Infrastructure and Transport, Ministerial Decree No. 223 1992). Subsequently, new restraint systems, including crash attenuators and special terminals, were introduced, accompanied by new indices and parameters for classifying and evaluating their performance. These include the Containment Level (Lc), Acceleration Severity Index (ASI), and later the Theoretical Head Impact Velocity (THIV) parameter for assessing the impact severity (EN 1317-1 and EN 1317-2, 2010).

In adherence to European standards mandating CE marking, road restraint systems must undergo rigorous crash testing prior to deployment. These tests validate essential aspects such as the system's ability to contain vehicles as designed, to redirect them correctly on the roadway after impact, and to mitigate injury risks by limiting deceleration for occupants of light vehicles. Based on these tests, systems are classified into performance categories or containment classes (see Table 1).

The containment level in Table 1 indicates the system's capacity to contain a vehicle, expressed based on vehicle mass (M), speed (v), and impact angle (φ): $L_c = 1/2 \cdot M \cdot (v \cdot \mathrm{sen}\varphi)^2$. However, national regulations define the minimum containment level required, considering factors like traffic type, speed limits, roadside hazards, and others (e.g., Budzyński and Antoniuk, 2017). The 'L-Class' for vehicles weighing 1.5 to 2 tons is introduced to enhance safety on European roads; this update requires a third test using a mid-sized vehicle for H-Class barriers (refer to Table 1), aimed at raising safety standards for middle-class vehicles. Consequently, H-class barriers are assessed with specific heavy vehicles for each class and undergo a standardized test using a small passenger car applicable to all classes. In turn, Table 2 shows the impact severity levels calculated by assessing the maximum permissible values of ASI and THIV (EN 1317-1, 2010).

In the context commonly used, ASI parameterizes acceleration levels experienced by the vehicle occupants with seat belts fastened, measuring inertia force near the vehicle's center of gravity during impact. THIV symbolizes the theoretical head impact velocity against an interior vehicle surface post-impact, assuming occupant and vehicle speed match pre-impact, and uninterrupted head motion during vehicle collision. Other key parameters encompass:

- the working width (i.e., the space that the restraint system occupies horizontally while accounting for any lateral movement caused by external forces; eight classes have been established: W1 ≤ 0.6 m, W2 ≤ 0.8 m, W3 ≤ 1.0 m, W4 ≤ 1.3 m, W5 ≤ 1.7 m, W6 ≤ 2.1 m, W7 ≤ 2.5 m, W8 ≤ 3.5 m);
- the dynamic deflection (i.e., the maximum lateral dynamic displacement of the traffic-facing restraint system under dynamic forces, thus assessing energy absorption, redirection, and vehicle occupant safety);
- the vehicle intrusion (i.e., the maximum vehicle deviation dimension of the impacting vehicle from the traffic face of the vehicle restraint system; testing carried out in compliance with EN 1317-2 (2010) measures it to the furthermost part of the heavy vehicles which includes a notional load having the width and length of the vehicle platform and a total height of 4 m from the ground).

Table 1. Containment levels and crash test specifications

Containement class	Containment level	Crash test*	Vehicle type	Test conditions		
				Vehicle mass (t)	Speed (km/h)	Angle of impact (degrees)
normal	N1	TB31	light	1.5	80	20
	N2	TB32	light	1.5	110	20
		TB11	light	0.9	100	20
high	H1	TB42	non-articulated truck	10	70	15
		TB11	light	0.9	100	20
	L1	TB32	light	1.5	110	20
	H2	TB51	bus	13	70	20
		TB11	light	0.9	100	20
	L2	TB32	light	1.5	110	20
	H3	TB61	non-articulated truck	16	80	20
		TB11	light	0.9	100	20
	L3	TB32	light	1.5	110	20
Very high	H_4a	TB71	on-articulated truck	30	65	20
		TB11	light	0.9	100	20
	L_4a	TB32	light	1.5	110	20
	H_4b	TB81	articulated truck	38	65	20
		TB11	light	0.9	100	20
	L_4b	TB32	light	1.5	110	20

Note: Information is based on data presented in EN 1317-1 and EN 1317-2 (2010)

Table 2. The impact severity level by class

Parameter	Formula	Class		
		A	B	C
ASI	$ASI(t) = \sqrt{\left(\frac{a_x}{12 \cdot g}\right)^2 + \left(\frac{a_y}{9 \cdot g}\right)^2 + \left(\frac{a_z}{10 \cdot g}\right)^2}$ $a_x(t)$, $a_y(t)$, $a_z(t)$ are the acceleration components, varying over time, determined over a moving interval of 50 ms, while the denominators represent maximum tolerable accelerations by the human body.	ASI ≤ 1.0	1.0 ≤ ASI ≤ 1.4	1.4 ≤ ASI ≤ 1.9
THIV[1] [km/h]	$THIV(t) = \sqrt{v_x^2(t) + v_y^2(t)}$ $v_x(T)$ and $v_y(T)$ are the relative velocities (in km/h) of the body with respect to the vehicle, referenced to the x and y axes.	THIV ≤ 33	THIV ≤ 33	THIV ≤ 33

[1] as for the THIV parameter, regulations prescribe a maximum value of 33 km/h for safety barriers and 44 km/h for attenuators and terminals

Among safety barriers, median barriers are a critical component of the road infrastructure, especially on high-speed highways and multi-lane roads, serving to separate opposing traffic flows (Sklet, 2006). They play a pivotal role in enhancing road safety by preventing head-on collisions caused by reckless overtaking, poor visibility, wrong-way driving, loss of control, and crossing into the path of oncoming traffic. Additionally, they reduce cross-median crashes, which are often attributed to the elevated speeds commonly observed on divided highways and decrease the risk of crashes caused by drivers drifting into the wrong lane due to distractions, drowsiness, or other factors (Graham et al., 2014). In the event of a collision, safety barriers are designed to absorb and dissipate the kinetic energy of the impact, thereby minimizing the severity of injuries to vehicle occupants. Median safety barriers come in various designs, including concrete barriers, cable barriers, metal-beam guardrails, and even vegetation. Concrete barriers, unlike cable barriers and metal-beam guardrails, are typically rigid with minimal deflection. They redirect rather than absorb impact energy. However, rigid concrete barriers rarely need repair or maintenance, making them a durable option (Sklet, 2006). The choice of barrier type depends on factors such as road design, traffic volume, and safety requirements (Russo and Savolainen, 2018). These barriers have distinctive features that enhance their effectiveness. Additionally, median barriers often incorporate reflective materials to improve visibility, particularly at night or during adverse weather conditions. Some median barriers may also include openings or gates to allow emergency access.

Given the relevance of the topic of road safety (e.g., Khan & Das, 2024; Ambros et al., 2019), a thorough literature review has been crucial in identifying existing research on the topic, highlighting unexplored areas, and uncovering the literature gap, thereby guiding future research directions and ensuring the study's contribution to the field. In scientific literature, research covers some aspects related to median barriers (see Section 2 for the related research). These studies explore various facets, including barrier design and performance (Wu et al., 2009; Wang et al., 2018; Shaffie et al., 2023), crash analysis and testing to refine barrier designs (Karunarathna et al., 2024; Calvi et al., 2023; Qawasmeh and Eustace, 2021; Chell et al., 2019; Molan et al., 2019; Russo and Savolainen, 2018), and maintenance and durability of median barriers, including the effects of weather, traffic conditions, wear and tear on barrier effectiveness (Gitelman and Doveh, 2022; Silvestri Dobrovolny et al., 2021). Additionally, the economic feasibility and effectiveness of different median barrier designs and installation strategies (Miaou et al., 2005; Kim et al., 2018), human factors associated with median barrier effectiveness, including driver behavior, perception, and response to these safety features (NCHRP Report 600, 2012; Zou and Tarko, 2016), and innovative technologies to enhance the performance of median barriers (Yang et al., 2019; Dinnella et al., 2020) are discussed. Researchers also evaluate regulatory compliance. Overall, research on median barriers is multidisciplinary and serves the critical purpose of continually enhancing road safety and reducing the severity of crashes on highways and multi-lane roads.

Considering the current challenges related to road safety and the limitations of existing road barrier systems, this paper introduces a pioneering system of road barriers designed to mitigate crashes and enhance overall traffic safety. Specifically, the paper presents the National Dynamic Barrier Anas (NDBA 2.0), a concrete median barrier developed by the Italian National Road Agency (ANAS), responsible for managing highways and roads in Italy. The NDBA 2.0 barrier (second generation) with variable length represents the initial release within a new line of safety barriers belonging to the NDBA family (Dinnella et al., 2020). However, it differs from the others by having a single module length of only 200 cm, specifically designed to address various complex situations definitively. The NDBA 2.0 barrier possesses distinctive characteristics and performance, fundamentally transforming the conventional approach to scheduled maintenance work. It adapts to the road infrastructure, reversing the traditional practice observed until now. The versatility of its length allows it to adapt to various installation requirements encountered during median barrier maintenance interventions.

After a brief overview of the literature on key areas in contemporary research related to safety barriers, the paper details the features and benefits of the NDBA 2.0 median barrier. It presents the main results of crash tests, possible configurations for the NDBA 2.0 on road curves, and technical specifications for tolerances and pull-out tests. Concluding remarks emphasize the need for ongoing innovation and collaboration to maximize the NDBA 2.0's impact on road safety worldwide.

2. Literature review

In the context of transport infrastructure, the effectiveness of median safety barriers has garnered considerable attention (Liu, 2020; Graham et al., 2014). These barriers, designed to separate opposing traffic flows, play a pivotal role in preventing cross-median crashes, thereby safeguarding the lives of motorists and passengers alike (Russo and Savolainen, 2018). Over the years, the design and technology of median safety barriers have evolved significantly, driven by advancements in materials and engineering principles (Liu, 2020; Graham et al., 2014). Comprehensive crash tests have been instrumental in assessing their performance, helping to establish standardized safety measures and regulations (Gitelman and Doveh, 2022).

One recurring theme in recent research on median safety barriers is the evolution of barrier materials and design. Advances in engineering and materials science have enabled the development of innovative barrier systems that are not only highly effective in crash scenarios but also environmentally sustainable (Zou et al., 2014). Many urban elevated roads use concrete block median barriers, supported solely by their own weight. However, these barriers often lack adequate support and connection, making them susceptible to overturning or shifting during vehicle collisions (Russo and Savolainen, 2018). Such failures can result in vehicles entering opposing lanes, causing severe crashes. To address these issues, Wu et al. (2009) used LS-DYNA to create a car-barrier collision model and designed a new median barrier model with interconnected concrete blocks. Simulations demonstrated that these improved barriers enhance traffic safety, even under a 2-ton vehicle, 60 km/h impact velocity, and 20-degree collision angle on urban elevated roads. In turn, Wang et al. (2018) developed a probability-based analysis approach to evaluate the performance of concrete median barriers during vehicle crashes, addressing the inherent randomness in such events. Traditionally, reliance on physical crash tests with a pass/fail method has limited our understanding. In this research, parameters like impact angle and vehicle weight were treated as random variables. Nonlinear finite element analyses of a standard pickup truck were conducted to calculate crash responses, and efficiency was improved using radial basis functions (RBFs) for metamodels. Monte Carlo simulations were then applied to determine the failure probability, proving the efficiency of this approach, especially for computationally expensive simulations. This study significantly enhances our ability to assess concrete median barriers in road safety. Shaffie et al. (2023) studied the rolling barrier system on straight and curved roads. Rolling barrier systems are safety devices that not only absorb shock energy but also convert it into rotational energy, effectively preventing fatal crashes. These barriers are especially important in high-collision areas, guiding vehicles safely back onto the road or bringing them to a stop. This study evaluated the effectiveness of rolling barrier systems on both straight and curved roads, focusing on their implementation in high-risk areas. Four types of rolling barriers were identified: straight roadside, curved roadside, steep roadside, and median barriers. Each type is designed to enhance safety on specific road types. Rolling barriers play a crucial role in improving road safety and reducing crashes and fatalities. Understanding these advancements is critical for ensuring the continual improvement of barrier design and their effect on road safety.

Crash analysis and testing constitute another prominent area of research focus. In recent years, many countries have introduced (2+1) roads to their networks, yet limited research explores how different design aspects, like median separation, influence driver behavior and performance. Contemporary studies frequently utilize advanced simulation techniques and real-world crash data to evaluate the effectiveness of median safety barriers (Calvi et al., 2023; Qawasmeh and Eustace, 2021) and to enhance barrier designs and standards (Chell et al., 2019; Molan et al., 2019).

In this perspective, Karunarathna et al. (2024) implemented a simplified simulation technique, segmenting the barrier system into an Impact Zone and a Rigid Zone, a novel approach for concrete crash barriers. The numerical model was validated using data from a previous experimental crash test, accurately predicting key performance parameters of the barrier. This simulation also provided insights that were difficult or impossible to obtain from experimental tests, such as internal energies and exit angles. The study explored the advantages of using energy-absorbing concrete over traditional concrete to mitigate occupant risks. The results comparison between the numerical models and experimental tests demonstrated the reliability of these models for simulating vehicle-barrier collisions, aiding in the assessment of current barrier designs and the development of new designs to improve road safety. In turn, Calvi et al. (2023) conducted a driving simulator study with 46 participants on a rural road in Poland, analyzing four median separation types: double-line markings, reflective elements, flexible guideposts, and cable barriers. Results showed significant impacts on driving behavior, with cable barriers leading to greater distance from the median. This study underscores simulation's potential in enhancing (2+1) road safety and behavioral models. Qawasmeh and Eustace (2022) evaluated the effectiveness of cable median barriers (CMBs) in preventing cross median crashes (CMCs) and related casualties in the United States. Their analysis of 12 State studies demonstrated CMB effectiveness, with reductions ranging from 24% to 93% for fatal and serious injury crashes and 50% to 91% for total cross-median crashes. However, some studies noted increases in possible injury and property damage only crashes.

Based on median-related crash data, Russo and Savolainen (2018) compared various median barrier types on freeways to assess safety performance. Their findings indicated that concrete median barriers resulted in fewer penetrations, but more severe crashes compared to cable barriers. They suggested that rigid barriers might be preferable in cases of limited available width, where cable barriers lack deflection capacity. Further investigations highlighted limitations in European crash testing regulations concerning vehicle occupants and standardized safety measures (Chell et al., 2019), offering insights into optimizing barriers for different traffic scenarios and environmental conditions. Molan et al. (2019) analyzed the impact of geometric variables on median traffic barrier performance on US interstate roads. Their study revealed that barrier height, type, and post-spacing significantly influenced crash severity. Concrete barriers under 0.8128 meters (32 inches) and cable barriers over 0.762 meters (30 inches) exhibited distinct trends in crash severity. W-beam barriers with specific post-spacing were linked to reduced fatalities and injuries. Additionally, the study suggested implementing flare barriers instead of parallel barriers to decrease crash occurrences in practical applications.

Median barriers require regular inspection and maintenance to ensure durability and effectiveness in enhancing road safety and preventing cross-median crashes. In-situ concrete barriers typically demand less installation space and infrequent maintenance. Conversely, steel guardrails, while capable of deflecting, require a broader median and more frequent upkeep, posing crash risks during maintenance roadwork. Gitelman and Doveh (2022) compared the safety performance of various median barrier types on Israeli highways. They examined four types: step-shaped in-situ, pre-cast concrete, steel guardrails, and old NJ-shaped in-situ barriers. Step-barriers showed better safety levels than NJ-barriers on dual-carriageway roads and sometimes outperformed others. On motorways, step-barriers were as safe as NJ-barriers and pre-cast barriers, while steel guardrails excelled, especially with traffic volumes above 40,000 vehicles. Economic evaluations favored replacing old NJ-barriers with step-barriers on dual-carriageway roads and steel barriers on motorways, enhancing overall road safety. Concrete median barriers, crucial for preventing cross-median crashes, can worsen flooding in flood-prone regions. Silvestri Dobrovolny et al. (2021) researched barrier designs with openings to mitigate this issue. Through finite element simulations and lab tests, they assessed hydraulic efficiency. A single-slope profile median barrier with a large scupper passed crash tests and met safety standards. Implementing this design in flood-prone areas could reduce flooding severity, lower risks to drivers, and minimize flood damage to highways and nearby areas.

Evaluating the economic viability and efficiency of various median barrier designs and installation methods through cost-benefit analysis is another significant area of research in transportation and road safety. This analysis aids policymakers, engineers, and researchers in making informed decisions about which barrier designs and installation strategies offer the best balance between safety and cost-effectiveness. Minor changes to median barrier installation guidelines occurred over an extended period (Graham et al., 2014). Recognizing the need for updated guidance, research projects have been initiated to enhance these guidelines, particularly for high-speed, multilane highways. Miaou et al. (2005) developed new guidelines and presented modeling and benefit-cost analysis findings, focusing on interstates, freeways, and expressways with four or more lanes and speed limits of about 90 km/h or higher. They performed a preliminary benefit-cost analysis for concrete and high-tension cable barriers, highlighting limitations and potential for future research. In South Korea, increased highway speeds have heightened collision risks with road barriers, particularly concrete median barriers (CMBs), leading to fatalities. To improve current CMBs, Kim et al. (2018) introduced new designs to reduce fragmentation upon vehicle impact. The novel concrete median barrier (CMB) with shock absorbers, known as Hi-CMB, significantly reduced concrete fragmentation by 99% compared to existing CMBs in South Korea. This design, incorporating reinforcement, section expansion, and shock absorbers, enhanced impact resistance, especially for heavy trucks, offering a more effective solution to mitigate road barrier collisions.

To assess the effectiveness of median barriers considering human factors such as driver behavior, perception, and responses, tools have been developed. These tools aim to integrate road user characteristics into road system design, providing valuable insights for highway designers, traffic engineers, and safety practitioners (e.g., NCHRP Report 600, 2012). Awareness and documentation of these factors are crucial because subsequent highway improvement projects may increase highway speeds, necessitating greater sight distance requirements. Zou and Tarko (2016) explored the concept of "crash conversion" by road barriers, which involves replacing high-risk collisions with less severe ones. Unlike previous research focusing on specific crash types or overall barrier effects, this study investigated the probabilities of various crash events under different road and barrier conditions. Using crash data, a model estimated changes in these probabilities, indicating that median concrete, steel guardrails, and cable barriers influence the likelihood of different crash outcomes. This research enhances our understanding of barrier safety benefits, aiding engineers in designing more effective barriers and assisting researchers in evaluating their performance (Pitblado et al., 2016).

Despite the widespread adoption of concrete (rigid) and W-beam (semi-rigid) guardrails worldwide (Yang et al., 2019), innovative technologies have revolutionized median barrier performance, significantly enhancing roadway safety. Advanced materials such as carbon fiber composites offer superior strength-to-weight ratios, improving impact resistance. Sensor-integrated barriers enable real-time monitoring and automated alerts for maintenance needs. Additionally, modular barrier systems enhance versatility and ease of installation, optimizing traffic management on modern roadways. As introduced in section 1, Dinnella et al. (2020) developed the NDBA concrete road safety barrier, featuring an innovative anchorage system using "C" steel profiles and HEM 100 steel profiles for linking modules. Numerical simulations and full-scale crash tests demonstrated its containment level of CL = 725 kJ (H4b class) and ability to withstand two successive heavy vehicle impacts. This barrier enhances safety for light vehicle occupants, making it suitable for high-traffic motorways with limited working width requirements.

In conclusion, while the literature review on safety barriers may not be exhaustive, it sheds light on the multifaceted challenges in this field, encompassing various barrier types, functions, and factors influencing their effectiveness. Nonetheless, it lays the foundation for designing innovative solutions to address current road safety barrier challenges. An ongoing focus in current literature revolves around the adaptability of median safety barriers. Researchers actively explore the effective barrier deployment on curved road sections, considering technical requirements for tolerances and stability in diverse road scenarios (La Torre et al., 2016). This underscores the necessity for flexible barrier solutions capable of accommodating various roadway geometries. In this perspective, The NDBA 2.0 variable-length barrier, the subject of this paper, represents a pioneering advancement within the NDBA family, tailored for median barrier applications. Its unique design, with individual module lengths of just 200 cm, fills a significant gap in addressing complex roadway scenarios.

In the subsequent sections, this paper introduces the Italian NDBA 2.0 median barrier, marking a substantial stride in enhancing the safety standards of road infrastructures both domestically and globally.

3. Insights on the variable-length NDBA 2.0 median barrier

The NDBA 2.0 heralds a shift away from conventional practices, adapting to road infrastructure and fundamentally transforming the traditional approach to scheduled maintenance. With its variable length, the NDBA 2.0 epitomizes the concept of a dynamic barrier, offering the flexibility to adjust anchor configurations to suit various roadside designs, considering factors such as available space, road type, and traffic characteristics. Additionally, it can accommodate diverse installation requirements, particularly during median barrier adjustments in road infrastructure. Moreover, the superior mechanical performance of NDBA barriers allows for installation in challenging conditions, such as existing motorways with narrow median strips (Pitblado et al., 2016).

The NDBA 2.0 single-wire road safety concrete barrier, installed on a concrete curb, features a maximum base length of 68 cm (with a head width of 19 cm) and a total height of 120 cm (see Fig. 1). Each 60 cm modular element weighs 5650 kg and is made of vibrated concrete with a strength class of C40/50 (exposure class XC4, XD3, XF4, and consistency class S5), using cement type 52.5 R and washed, sifted quarry aggregates. It is reinforced with a FeB44K steel cage and fiber reinforcement. The barrier includes six tubular elements and two head profiles of hot-dip galvanized S275Jr steel. A minimum installation length of 72 meters is required, and it belongs to performance class H4b W2 (EN 1317-1, 2 and 3, 2010).

The variable-length NDBA 2.0 median barrier retains the aesthetic design of the standard NDBA barrier but has a 200 cm module length (Dinnella et al., 2020). This design addresses complex issues, especially those encountered during median barrier replacements at ANAS road construction sites:

- Installation in the vicinity of transverse joints: frequently, the anchoring bolts of the NDBA 2.0 concrete barrier end up near or on bridge and viaduct transition decks, or on transition slabs between two structures.
- Continuity issues between modules: ensuring proper connection between NDBA 2.0 modules, whether installed at different times or on varying supports (e.g., road pavements and structures), requires appropriately sized steel casings. These casings, however, pose aesthetic challenges as they fail to provide the desired visual continuity mandated by Italian standards for road construction (Ministerial Decree No. 6792, 2001) and safety barriers (e.g., ANAS guidelines on road safety barriers, 2019; Ministerial Decree No. 2367, 2004).
- Installation on circular curves: the support plane of the devices becomes inclined due to the slope of the inner edge towards the median barrier, resulting from the different heights of the road edges.

The main issue stems from the fixed length of the standard NDBA barrier modules (asphalt, concrete, and bridge), all measuring 600 cm. Across the road and highway network, transitions between different types of barriers are achieved using special components known as transition elements. These elements primarily restore continuity between successive barriers and distribute deformations during an impact near the transition. The CEN TC226/WG1 (2023) declared transitions as components that cannot receive CE marking, classifying them as non-manufactured components. Therefore, under the current regulatory framework, there is no obligation in Italy to test and certify transitions.

Transitions are currently installed based on results obtained from finite element method simulations (e.g., Karunarathna et al., 2024). Regrettably, certain technical and regulatory shortcomings often result in the improper installation of transitions along the edges of road infrastructure. This improper installation could potentially pose dangers in the event of an impact. Industry experts are particularly concerned about this issue, as crashes, including fatal ones, frequently occur on these elements. Consequently, addressing this matter before judicial authorities becomes a complex undertaking (Liu, 2020; Pitblado et al., 2016).

The NDBA 2.0 barrier was designed to eliminate the need for future simulations in the design and verification of transitions between different barriers. As a result, this median barrier underwent testing in real-world H4 class conditions and now holds the CE marking. The operational procedures used during actual crash test trials, which included a test configuration consisting of a sequence of all elements with a length of 200 cm, enabled the entire NDBA family's product range, featuring variable module lengths from 200 cm to 600 cm, to achieve CE marking. Essentially, when connecting a new NDBA barrier to an existing one or joining different modules near expansion joints on bridges and viaducts, creating a special piece ranging from 200 cm to 600 cm in length is sufficient, without requiring additional simulations, as it already carries the CE marking. This new approach represents another advancement in safety devices at both national and international levels to enhance road infrastructure safety.

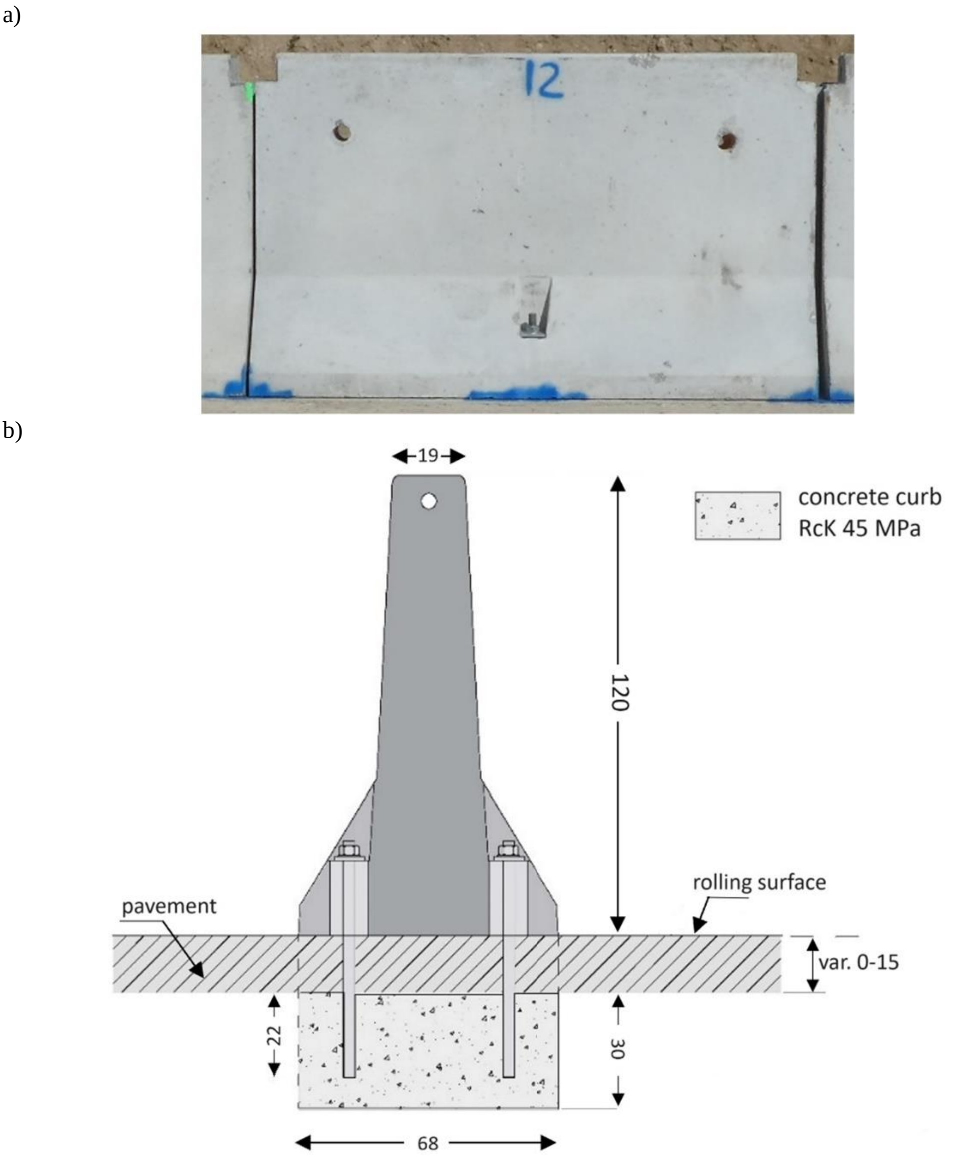

Fig. 1. Construction details: a). NDBA module; b). Installation configuration in the presence of asphalt conglomerate above the curb. Note: lengths in centimeters. Source: designs and photos are made by the Authors

Some of the general benefits of the short-length configuration of the NDBA 2.0 are as follows:

- Ease of construction: the barrier elements can be easily constructed using standard formwork, supplemented with movable side forms that adjust to the module length, simplifying the construction process;
- Unchanged metalwork: no structural elements of the standard NDBA barrier, such as pockets and profiles, are altered;
- Consistent reinforcement: only the length of longitudinal reinforcement bars requires modification; shear-working stirrups remain unchanged;
- Versatility: variable-length NDBA modules can interchangeably serve in both concrete configurations for parapet anchoring and asphalt versions for embankment anchoring;
- Testing configurations: a test configuration utilizing 200 cm elements accommodates all necessary setups to address issues encountered during execution phases.

Before the introduction of variable-length NDBA barriers, the typical approach to ensuring continuity between adjacent barriers involved installing removable openings or incorporating transitional and connection elements. The variable-length modules of NDBA 2.0, applicable both on embankments and road structures, effectively maintain continuity between two NDBA installations executed at different times. This scenario is common because enhancements or upgrades to NDBA median barriers often occur independently of adjacent embankment interventions.

The presence of longitudinal joints and varying span lengths on bridges and viaducts complicates efforts to adopt barrier configurations that accurately reflect those outlined in crash reports and installation manuals. Consequently, variable-length NDBA barriers provide a flexible solution to address these challenges and ensure consistent safety standards across different sections of the road infrastructure. Often, it is necessary to refrain from installing a pair of anchor bolts to avoid connecting two different spans that, subjected to typical vibrations and temperature fluctuations, could damage the anchoring of the barriers, compromising their proper functioning.

The solution often adopted is to use only 4 out of the 6 anchor bolts, all on the same span, or to use a steel enclosure properly sized. The adoption of this latter element, considered as a special component, thus simulated but not tested, inevitably causes issues in the road network due to the lack of aesthetic continuity of the installed devices (Pitblado et al., 2016). In essence, variable-length NDBA modules for installation on bridges and viaducts provide the following benefits:

- preventing anchor bolts from being positioned above transverse joints;
- eliminating the need for simulations or calculation reports to ensure barrier functionality, even when certain anchor bolts are absent;
- mitigating the risk of anchor bolts being positioned above transition slabs;
- ensuring alignment of the NDBA barrier joint with the transverse joint of bridges and viaducts;
- allowing for the restoration of the NDBA-curb system connection after crashes by inserting variable-length modules to establish new anchor bolts in a different position from the previous installation configuration.

In many road infrastructures managed by Anas, constructed decades ago, a concrete curb is present on the inner edge of the median barriers. Existing concrete barriers rely on friction for support from the curb, while steel barriers have posts inserted into pockets embedded in the curb. When upgrading to the more performance-oriented NDBA barriers, challenges arise primarily from the difficulties in demolishing the existing curb and subsequent ancillary works. These challenges are often complex and costly, affecting both construction timelines and budgets.

The NDBA barrier effectively addresses these issues. If the existing curb conditions match those of the test curb, adapting the barriers can proceed without demolishing the curb. This approach offers significant benefits, including cost reduction, time savings, less material sent to landfills, environmental benefits from reduced vehicle traffic, lower risks for workers due to shorter timelines, and minimized inconveniences for users. For newly constructed curbs, if the designer chooses NDBA barriers based on design preferences rather than space constraints, the new curb should match the characteristics of the test curb. Any differences in size or mechanical properties necessitate performance verification of the curb-barrier system. This involves applying forces specified in the following section, with a maximum tensile force of 181 kN and a maximum shear force of 22 kN and documenting these details in the roadway enhancement project.

4. The crash test trials in Italy

The crash tests were conducted at the "CSI test Center" (IMQ Group) in Bollate, Milan, Italy, where a representative concrete curb of the road installation was prepared. The tests were performed in accordance with EN 1317 regulations parts 1 and 2 (2010). The NDBA 2.0 has successfully undergone an impact test sequence: first, by a light vehicle (900 kg) at a speed of 100 km/h and a collision angle of 20 degrees. Subsequently, with the barrier already damaged from the initial test, it was tested by a heavy vehicle (38 tonnes) at a speed of 65 km/h. Both tests were conducted and passed at the CSI testing center. The maximum displacement upon impact (W2) achieved in both tests earned the product its CE marking. On April 4th, 2023, a barrier of class H4b was installed on a concrete reinforced curb to conduct the test (CSI Test Report, 2023). The concrete curb in the impact area consists of a single foundation fixed to the ground, with a total length of 72 meters and a width of 68 cm. The TB11 test was not conducted because the NDBA 2.0 barrier in question is an integral part of a family of barriers as defined in the EN 1317-2 standard. The standard mandates testing the most severe condition (6 m elements) with a light vehicle for the TB11 test and the most deformable configuration (2 m elements) with a heavy vehicle for the TB81 test.

Regarding the installation of NDBA 2.0 module units in crash tests, each element of the NDBA barrier was installed on the test curb. Each element was anchored with two Ø30 anchor bolts (each with a diameter of 30 millimeters) inserted to a depth 0.22 meters, maintaining a specific center-to-center spacing as depicted in Fig. 1a. HEB 100 profiles, 90 cm in height, were used between the modules to accommodate greater displacement tolerance due to temperature variations.

Other key features of this barrier system include a 0.14-meter separation between the anchorage point and the curbside, a height of 1.2 meters, posts spaced at 2-meter intervals, and an overall length of 72 meters (i.e., 36 NDBA 2 m blocks). To ensure the barrier's integrity, the actual dimensions of its components used in the test were rigorously inspected and compared against the measurements and tolerances specified by the manufacturer. It was confirmed that all components meet the manufacturer's specifications and fall within the allowed tolerances. A thorough examination to confirm that the materials employed in the barrier align with the manufacturer's specifications was also conducted. Fig. 2 shows the detail of the installation of NDBA 2.0 modules (Fig. 2a) and the detail of the HEB 100 profile (Fig. 2b), compliant with the UNI 5397-78 series. Additionally, Fig. 2c shows the minimum dimensional characteristics of the curb required for the installation, where A indicates the position for brackets with a diameter of 12/25 mm, and B indicates the position for currents 4+4 with a diameter of 14 mm.

To test the most critical scenario for any configuration, a full-scale TB81 crash test was conducted using NDBA 2.0 concrete elements, each 2 m long. The installation spanned 72 meters, excluding terminals, and comprised 36 elements. The TB81 test was performed in accordance with the UNI EN 1317-2:2010 standard (see Table 1). A heavy vehicle (SCANIA 124L) weighing 38 tons, with a width of 2.55 meters and a platform height of 1.35 meters, impacted the barrier at a 20-degree angle and a speed of 65 km/h, achieving an operational width of W2 ≤ 0.8 meters, consistent with all tests within the NDBA family (Dinnella et al. 2020).

The impact resulted in the dynamic deflection of 0.2 meters (and normalized dynamic deflection of 0.2 meters), the working width of 0.8 meters (and normalized working width of 0.83 meters), the vehicle intrusion of 3.0 meters (class of vehicle intrusion: VI8 ≤ 3.5 meters), the maximum permanent deflection of 0.19 meters, permanent working width of 0.83 meters.

This expected yet unguaranteed result can mainly be attributed to specific factors identified through the test: the reduced module size of 2 m does not affect dynamic functionality upon impact; two anchorages per module provide sufficient resistance to impacts from both heavy and light vehicles; the connections between modules ensure suitable kinematic performance; the mechanical characteristics of the support are adequate for withstanding impact stresses (CSI Test Report, 2023). Therefore, any combination of modules with lengths ranging from 2 m to 6 m can be considered valid and directly applicable in the field, as tested.

Often, especially on bridges and viaducts, median barriers are installed on existing slabs with limited thickness (as little as 25 cm) and a pavement layer no thicker than 15 cm. To evaluate the performance of the NDBA 2.0 barrier on these slabs, a typical installation scenario was replicated in the laboratory, constructing a curb measuring 68 cm in length and 30 cm in height using C35/45 class material. Fig. 3 shows, in turn, possible typical installations on bridges and viaducts with transverse joints (Fig. 3a) and on minor crossing structures (Fig. 3b).

The anchoring bolts, located on three consecutive elements on both sides (six in total) of the NDBA 2.0 module unit, were equipped with strain gauge rosettes connected to a multitrack analog recorder with a sampling frequency of 200 Hz. This setup was used to measure the stresses transmitted by the barrier to the foundation curb. These rosettes measured the deformations (ε) of the material constituting the anchoring bolt, and through the stress-strain curve, the stresses transmitted by the anchoring bolt to the foundation curb were determined (Fig. 4). The indirect method provided a more precise way to calculate stresses compared to other methods, such as using load cells on the anchor bolt or a section of the curb. This is because it directly measures material deformation on the anchor bolt and is not affected by dynamic factors that can distort load cell readings.

The measured values in Fig. 5 indicate a maximum tensile force of 181 kN on anchor bolt no. 5 (Fig. 5a) and a maximum shear force of 22 kN on anchor bolt no. 2 (Fig. 5b). Therefore, these values should be used in assessments and validations for installations on existing sections with foundation structures that differ from those used in crash tests.

To implement device monitoring through data correlation with smart roads (Pompigna and Mauro, 2022), the NDBA approach can be applied in actual road installations by equipping a set of anchor bolts with sensors and gathering information, such as:

- identifying potential loosening of anchor bolts due to factors like traffic vibrations, structural settling, or adjustments;
- determining the type of vehicle involved and assessing potential structural damage after a recorded impact;
- enabling planning and execution of necessary immediate interventions based on this data.

For illustrative purposes, Fig. 6 shows some frames from the test sequence. The test vehicle collides with the device at module 12 (see frames from the test sequence in Fig. 6), is effectively restrained, and comes to a stop approximately 45 meters from the impact point. Following the test, the two successive blocks beyond the collision also sustained damage, with concrete pieces detaching, some weighing over 2 kg. The foundation was also damaged, resulting in cracks on the curb at the impact anchor bolt locations. Furthermore, there was deformation of fastenings extending from the two previous modules to the point of the vehicle's contact with the device. Notably, there was deformation of plates and washers along the impact blocks; however, no bottom pulls were broken.

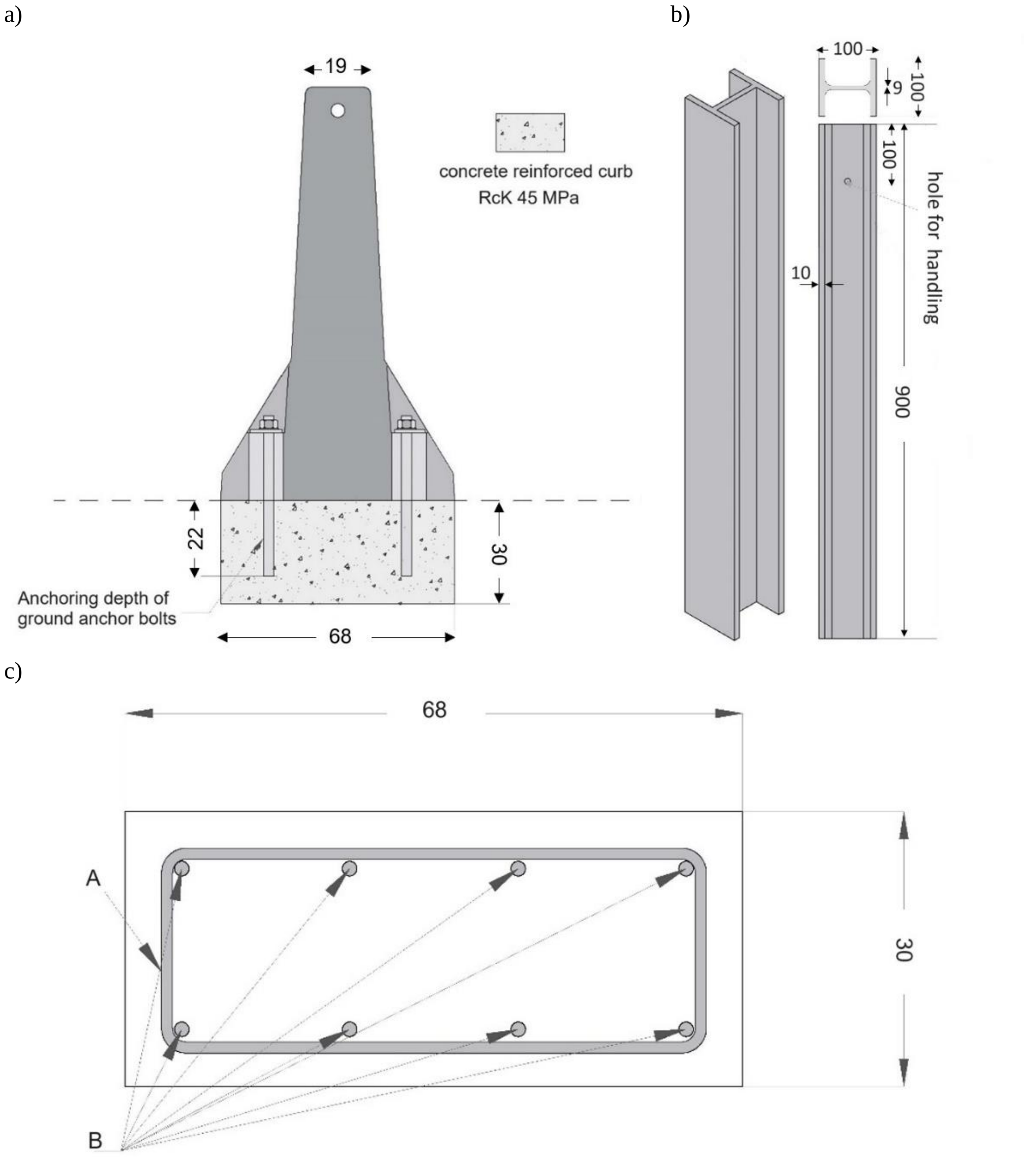

Fig. 2. Construction details: (a) NDBA module installation configuration; (b) HEB 100 profile; (c) Foundation curb used in real-life tests. Note: lengths in centimeters; A and B in Fig. 2c indicate the position for brackets with a diameter of 12/25 mm, and the position for currents 4+4 with a diameter of 14 mm, respectively. Source: designs and photos are made by the Authors

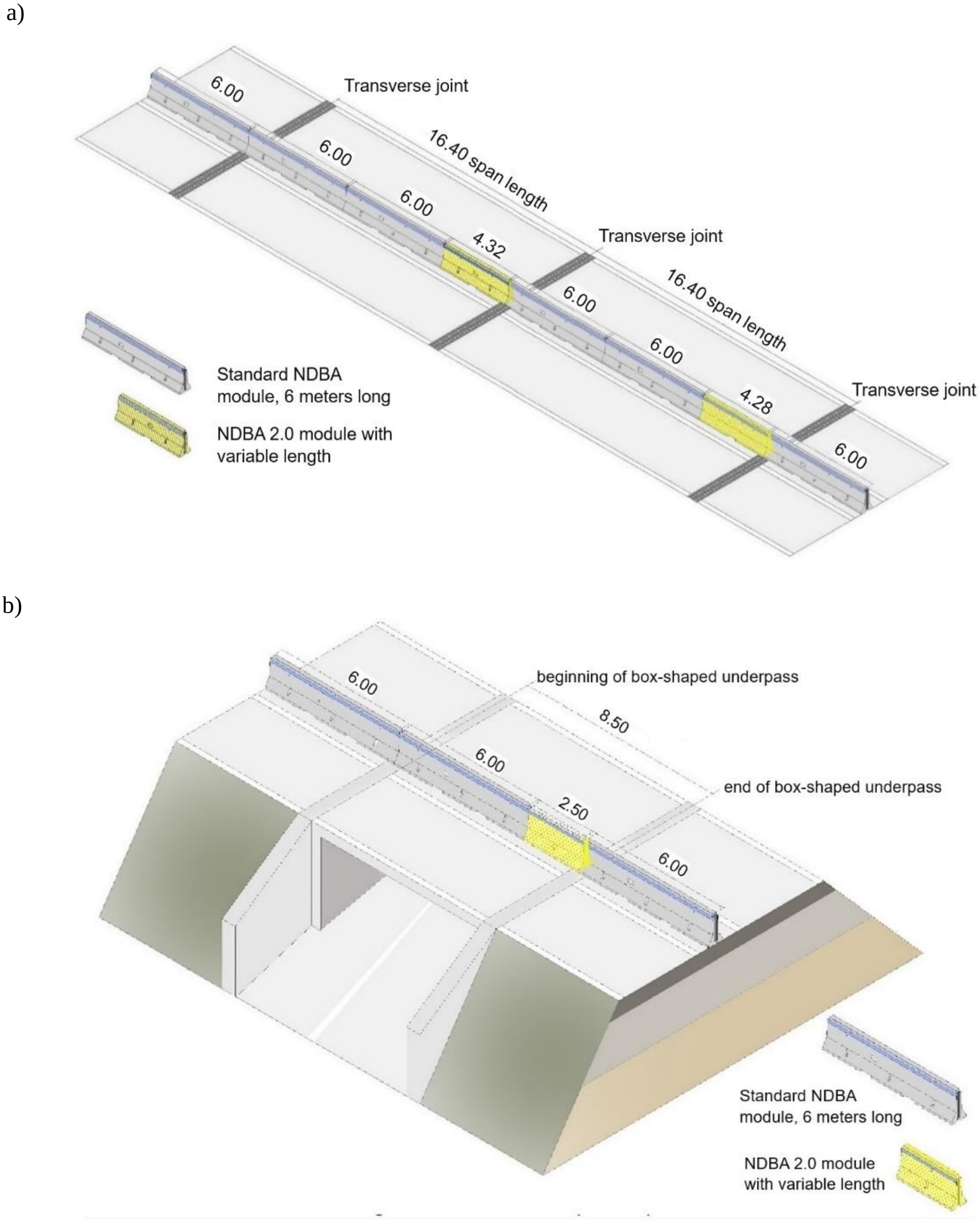

Fig. 3. Typical installation on (a) bridges and viaducts with transverse joints; (b) crossing structures. Source: designs and photos are made by the Authors

Fig. 4. Instrumented anchor bolts. Source: designs and photos are made by the Authors

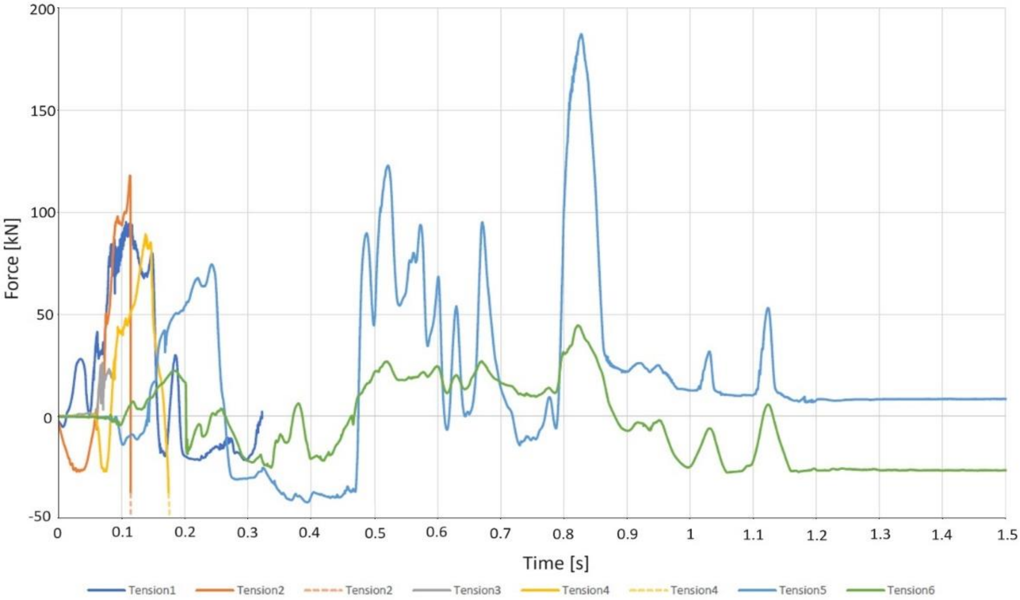

Fig. 5.a. Diagram: Axial force diagram on anchor bolt no. 5. Note: For anchor bolts no. 2 and 4, only the solid line in the graph is considered, as the dashed segment is deemed unreliable due to the yielding of the anchor bolt. Source: designs and photos are made by the Authors

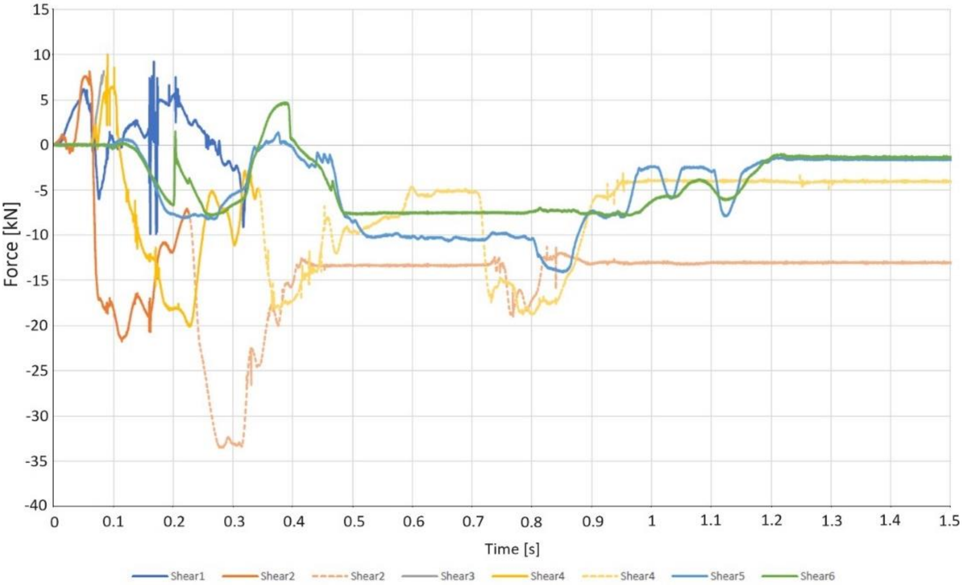

Fig. 5.b. Diagram: Shear force diagram on anchor bolt no. 2. Note: For anchor bolts no. 2 and 4, only the solid line in the graph is considered, as the dashed segment is deemed unreliable due to the yielding of the anchor bolt. Source: designs and photos are made by the Authors

5. The possible configurations of the NDBA 2.0

Following the results obtained from crash test trials, several possible configurations for the NDBA 2.0 barrier have been identified, along with the technical specifications for tolerances. According to Circular Protocol No 62032 (2010), the permitted tolerances for NDBA barrier installations pertain to the dimensions of the rolling surface relative to those of the installation plane. The tolerance for installing NDBA 2.0 barriers is determined from the correlation between tests conducted on NDBA concrete barrier elements and crash test results. In all the crash test trials mentioned, consistent ASI B index and W2 working width were observed, demonstrating uniform performance across different configurations. Essentially, since the NDBA 2.0 barrier shares the same aesthetic form, performance levels, and mechanical characteristics as the standard NDBA barrier, the tolerances validated for the standard NDBA concrete barrier can be considered applicable (Dinnella et al., 2020).

The possible configurations include installation with the rolling plane higher than the laying plane, installation with the rolling plane lower than the laying plane, installation with bituminous conglomerate over the curb, and installation in circular curves. For installations where the rolling plane is higher than the laying plane, the barrier can be installed at a height ranging from 0 to -15 centimeters relative to the rolling plane (tolerance 0 to -5 cm). Conversely, for installations where the rolling plane is lower than the laying plane, the barrier can be installed at a height ranging from 0 to +15 cm relative to the rolling plane (tolerance 0 to 5 cm). Fig. 1b illustrates the installation configuration with an asphalt conglomerate layer above the curb, with a variable height from 0 to 15 cm. The described tolerance allows for selecting a horizontal installation plane for barriers, especially in circular curves or installations with staggered carriageways and rolling planes at different heights, without the need to tilt them, as previously required. Fig. 7 below provides a visual representation of a possible solution to these challenges. As mentioned earlier, transitions between the NDBA 2.0 barrier and the standard NDBA (asphalt and concrete) barriers are unnecessary. Any special piece needed for continuity in installations, such as a variable-length NDBA 2.0 barrier, comes equipped with CE Marking.

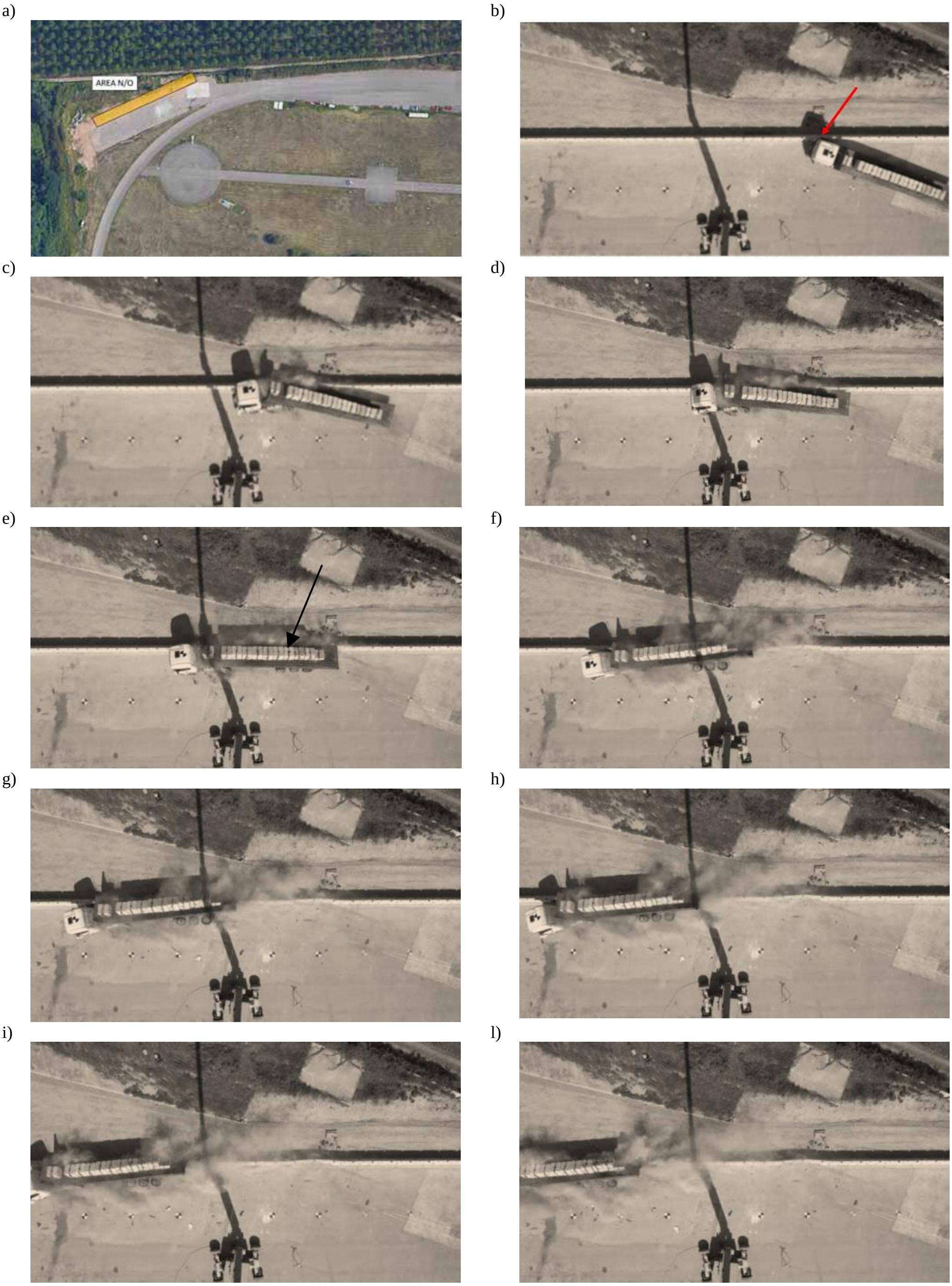

Fig. 6. Crash test: a). A view of the testing area; b). to l). Frames from the test sequence

To verify the maximum tensile strengths of the anchorages used during the TB81 crash test, it is necessary to conduct at least 10% of the pull-out tests on the total number of installed anchor bolts. Table 3 presents the results of two pull-out tests performed on the test curb under unconfined conditions. This testing method provides insights into the overall behavior of the anchoring system, considering the potential for concrete cone failure (see Fig. 8).

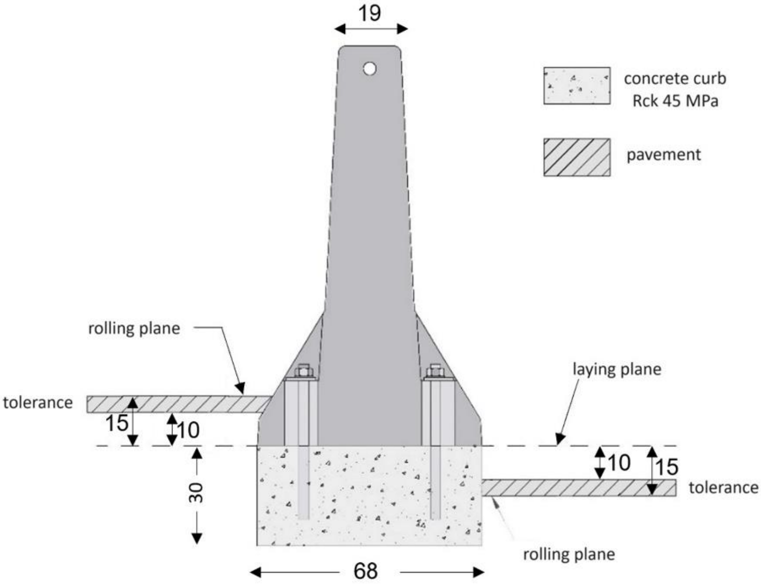

Fig. 7. Installation configuration in circular curves. Source: designs and photos are made by the Authors

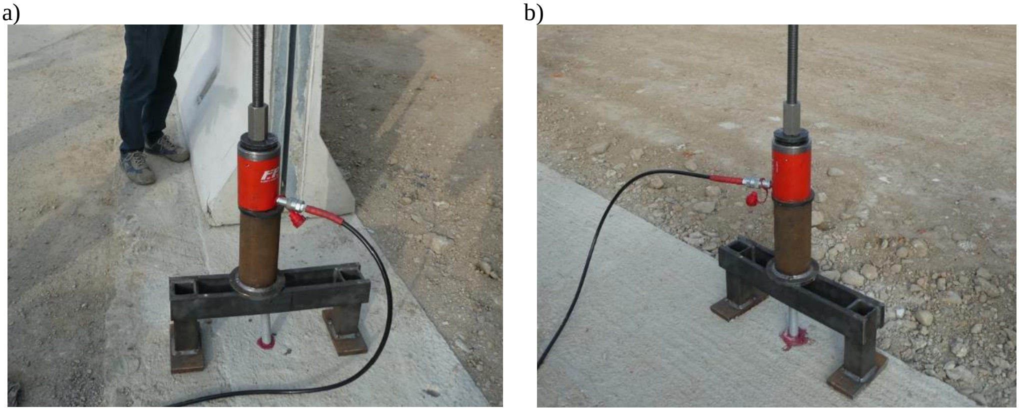

Fig. 8. The Pull-out tests: a) the first test; b) the second test

Table 3. The impact severity level by class

Test No	Maximum load [kN]	failure mode	note
1	286.4	foundation settlement	The curb is cracked, but the anchor bolt is intact.
2	264.5	foundation settlement	The curb is cracked, but the anchor bolt is intact.

6. Conclusions

The design and implementation of the NDBA 2.0 barrier mark a significant advancement in road safety technology, epitomizing adaptability and innovation made in Italy. Unlike traditional barriers, which require infrastructure modifications to fit their specifications, the NDBA 2.0 adapts seamlessly to existing road conditions. This flexibility not only simplifies installation but also ensures aesthetic and functional uniformity across different modules and supports, even when installed at different times and traffic conditions. By addressing installation challenges near transverse joints and reducing the reliance on specialized pieces and untested connections, Anas has taken a decisive step toward enhancing the safety and reliability of its road infrastructure.

One of the standout features of the NDBA 2.0 barrier is its variable-length modules, which offer unparalleled versatility. This adaptability is crucial for meeting diverse installation requirements across various road infrastructures. The ability to adjust module lengths within a specified range allows for tailored barrier configurations, ensuring optimal performance in different scenarios. Moreover, the NDBA 2.0 has been rigorously tested to meet CE marking requirements, demonstrating its compliance with stringent EU health, safety, and environmental standards.

The barrier's design facilitates ease of construction and compatibility with existing structural elements, significantly simplifying the installation process. By accommodating different anchoring methods and addressing specific challenges encountered during construction, the NDBA 2.0 reduces the need for extensive simulations during design and verification. This streamlines the implementation process, ultimately lowering installation and maintenance costs.

The NDBA 2.0's performance has been validated through rigorous crash tests, which simulate real-world impact scenarios. These tests have confirmed the barrier's ability to withstand significant forces, providing reliable protection for road users. The consistent achievement of an ASI B index and W2 working width across various configurations underscores the barrier's performance homogeneity and reliability.

From a road safety perspective, the NDBA 2.0 offers substantial advantages. Its design minimizes crash-related costs by reducing the severity of accidents, particularly near transition zones. The barrier's dynamic design allows it to adjust to varying road conditions and traffic volumes, overcoming common installation challenges on existing roadways. Its ability to be directly supported on the road surface wear layer eliminates the need for costly foundation structures, facilitating quick installation and reducing maintenance expenses. Anchoring with standard pile driving machines ensures operational efficiency and cost-effectiveness making it feasible even in limited spaces.

The NDBA 2.0's innovative design is further exemplified by its rigid connection solution between adjacent modular elements. Additionally, the barrier's internal cavity in the upper part allows for the passage of technological cables, enabling real-time communication with Anas Control Operating Rooms in case of damage. This smart feature facilitates the prompt dispatch of rescue teams, alerts users about potential dangers, and ensures swift traffic restoration.

The NDBA 2.0 barrier has earned recognition for its innovative design and performance, notably winning the STA Annual Awards for Technical Excellence in the "Best Innovative Project/Solution" category in 2023. This prestigious award highlights Anas' commitment to excellence in transport infrastructure and its dedication to enhancing road safety through cutting-edge technology.

In conclusion, the NDBA 2.0 barrier represents a significant leap forward in road safety and infrastructure management. Its adaptability, ease of installation, and robust performance make it a valuable asset for modern roadways. Continued research, collaboration, and widespread adoption of such innovative solutions are essential for further improving global road safety and operational efficiency. As Anas continues to push the boundaries of what is possible in transport infrastructure, the NDBA 2.0 barrier stands as a testament to the potential of intelligent design and engineering excellence.

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