Renewable Hybrid Roadside Barrier: Optimization of Timber Thickness

Huseyin Yorur,[a] Sedat Ozcanan,[b] Halil Ibrahim Yumrutas,[c,*] and Emre Birinci [d]

Researchers have recently focused on new and original roadside barriers that prioritize aesthetic, and environmental concerns by employing natural materials. In this study, the safety performance (Acceleration Severity Index (ASI), Theorical Head Impact Velocity (THIV)), structural performance (Working Width (W), Exit Angle (α)), and failure analysis (visual deformation) of a newly developed Renewable Hybrid Barrier (RHB) system at different timber thicknesses were tried to be determined by pendulum crash test and Finite Element (FE) models. The FE models were calibrated and validated based on pendulum crash test results, and then the most suitable timber thickness in terms of safety and structural performance was determined *via* FE analyses. The results revealed that as the timber thickness decreased, the safety parameters, such as ASI and THIV, decreased, thus the barrier safety increased. However, it was observed that the deflection and deformations in the barrier increased as the timber thickness decreased. In this sense, the safest and the most structurally durable barrier was determined through conducting virtual optimization tests. Studies on diversification of the usage areas of natural/renewable materials should be increased in the future.

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INTRODUCTION

One of the problems related to the increase in mobilization, especially in developing countries, is ensuring roadside traffic safety. To prevent or reduce the problems caused by traffic accidents, highway and traffic engineers make intense efforts and offer different solutions (Wright 1983; Roque *et al*. 2015; Ramiani and Shirazian 2020; Yumrutaş and Othman Ali 2022).

One of the solutions that serve this purpose is road restraint systems placed on the roadsides. There are various road restraint systems that are designated to redirect errant vehicles with a specified performance level and can provide guidance for risky/vulnerable roadsides such as sidewalks, bus stops, playgrounds, and petrol stations. These systems are guardrails, bollard systems, ditches, berms, fences, walls, planters, blockers, *etc.* They can be produced using different materials to serve different purposes. However, research studies have generally focused on the barrier types made of conventional materials such as concrete and steel. For this reason, steel guardrails, New Jersey concrete barriers, and cable barriers can be counted as barrier types that are generally accepted and frequently encountered in practice.

A few studies in the literature have focused on the use of only timber barriers or the reinforcement of timber barriers with steel or fiber additives (Lohrey *et al*. 1997; Ad 1999; Zhang *et al*. 2004, 2006; Bocchio *et al*. 2001; Leijten 2000, 2001; Davids *et al*. 2006; Kubojima *et al*. 2006; Watts and Morgan 2007; Faller *et al*. 2009; Marzougui *et al*. 2010; Wacker *et al.* 2010; Goubel *et al*. 2011; Cecháková *et al*. 2012; Pilia *et al*. 2012; Borovinšek *et al*. 2013; Bielenberg *et al*. 2014; Pilia and Maltinti 2014; Noda *et al*. 2016; van de Kuilen 2019).

Limited studies on new barrier types produced from innovative materials are available. Muller and Majerus (2002) explored the potential of recycled plastic bottles for use in roadside barriers and evaluated the effectiveness of the new barrier system employing computer software to reach the optimal solution. Amato *et al.* (2011) developed a new barrier type using low-cost building materials (stone and soil) to meet cost, aesthetic, and engineering requirements. The design consisted of linked steel gabions filled with stones, a type of structure generally used as a retaining wall but with different linkages. They observed the performance *via* real and virtual experiments. Anderson *et al*. (2012) added a flexible fabric material below the conventional guard rail and in front of the posts to provide a continuous protection system, especially for motorcyclists. They compared before and after crash statistics at a selected site and observed the contribution of the new material to existing guardrails in terms of performance. Atahan *et al.* (2002) manufactured guardrail posts from recycled materials and evaluated them for possible use in conventional steel guardrail systems. Static laboratory tests were conducted to determine the basic physical and mechanical properties of posts, and pendulum impact tests were performed to determine the dynamic response performance of the posts.

Recently, Yumrutaş *et al.* (2021) developed an innovative roadside barrier called "renewable hybrid barrier" (RHB) employing wood and sand material together. They conducted experimental pendulum crash tests and virtual tests to evaluate the efficiency of the novel barrier type. The results were successful for possible future novel barrier types. Yumrutaş and Ali (2022) developed renewable hybrid barriers using waste materials (slag and tyre). In this regard, they conducted pendulum crash tests to assess the performance considering the EN 1317 (2010) road restraint systems standard. The results indicated that hybrid barriers made of waste materials can be alternative to conventional barriers in terms of cost, environment, and aesthetics.

In this study, performance analyses for the normal (N2) containment level of wood material thickness in the renewable hybrid barrier (RHB) system, which was originally produced by Yumrutaş *et al.* (2021) using wood and sand, were revealed by virtual tests. In this context, verification and validation processes were completed based on the previous pendulum crash test data. After the model was verified, virtual full-scale tests based on the finite element method were applied for the TB 11 and TB 32 acceptance tests in line with the EN 1317 (2010) standard. The effects of timber thicknesses on the crash performance of RHBs were observed by considering the Acceleration Severity Index (ASI), Theoretical Head Impact Velocity (THIV), Working width (W), Exit angle (α)/exit box, and failure (visual deformation) parameters, and then the optimal timber thickness was determined.

EXPERIMENTAL

The Design of Renewable Hybrid Barrier

Renewable Hybrid Barriers (RHBs) comprise four main elements: timber, sand, concrete base, and steel frame. The concrete base is designed to separate timber materials from rainwater on the road platform. It is produced with C 30/37 grade cast *in-situ* concrete with the dimensions depicted in Fig. 1. The male and female parts enable interlocking with adjacent barriers, thus resisting impact energy together.

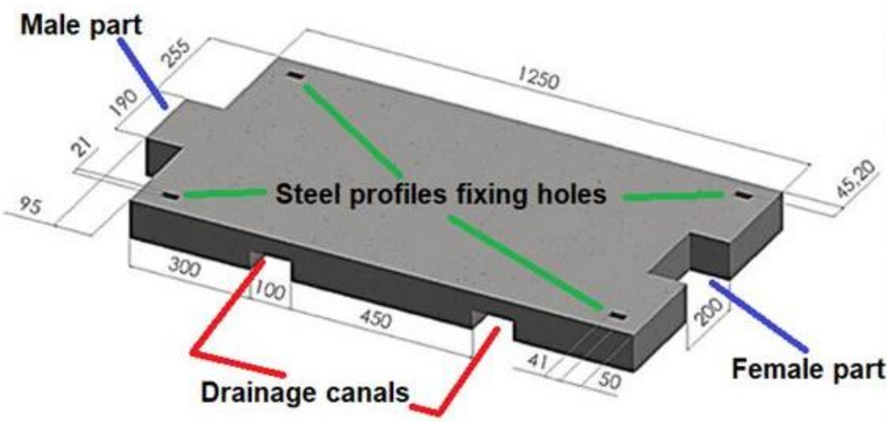

Fig. 1. Concrete base; all units are in mm

The steel frame that was made of S 235-grade rectangular section steel tube profile with $40 \times 20 \times 3$ mm^3 dimensions was used to fix timbers on it with screws and to give an F-shape form of RHBs (Fig. 2). They were inserted into the holes on the concrete base.

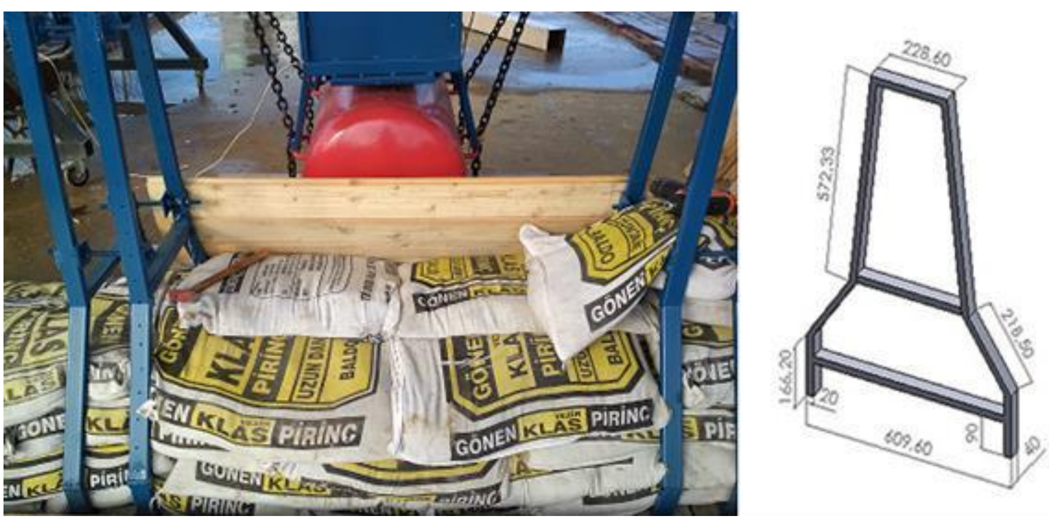

Fig. 2. Steel frame and the dimensions; all units are in mm

Wooden materials were produced from fir timbers (*Abies nordmanniana* subsp. *equi-trojani*) with thickness of 2, 4, 6, 8, and 10 cm. The half-lap method was applied to the joints of wooden timbers.

The main purpose of using sand in the design of RHBs is to benefit from the high energy absorption capacity of sand (Lambert *et al.* 2009; Sabet *et al.* 2009; Ho *et al.* 2013;

Sy Ho and Masuya 2013; Bhatti 2015; Chian *et al.* 2017) and to diminish the cost. Crushed stone sand 0 to 5 mm in dimensions was not filled inside RHBs directly but first filled into the bags and then placed in the RHBs from the bottom level to the top. In this way, scattering pieces of the sand could be prevented after any accident, thus preventing a probable subsequent accident.

For each crash test, 3 RHBs were employed, and the finished product is presented in Figure 3 with the dimensions (Yumrutaş *et al.* 2021).

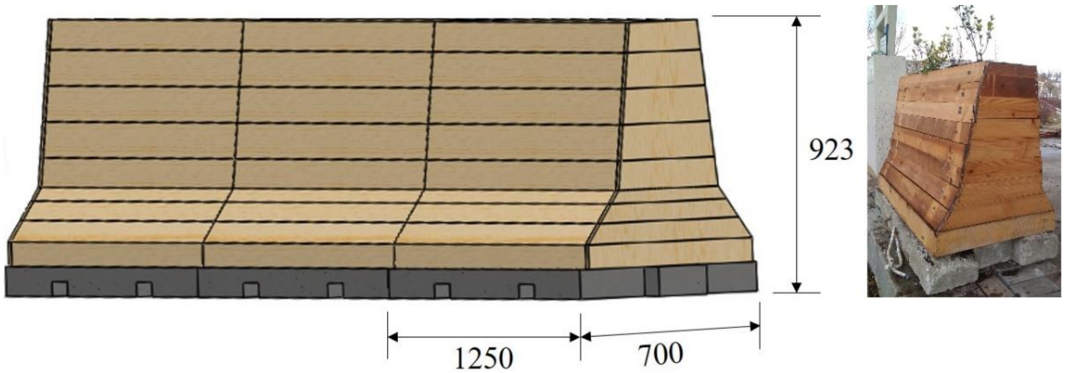

Fig. 3. The finished product of RHB; all units are in mm

Design and Concept of the Crash Pendulum System

The crash pendulum system includes a rigid frame, rammer, crane, and chains to suspend the rammer (Fig. 4). The pendulum rammer was lifted to a certain height with the help of a crane and released for free fall to generate the same energy for each experiment.

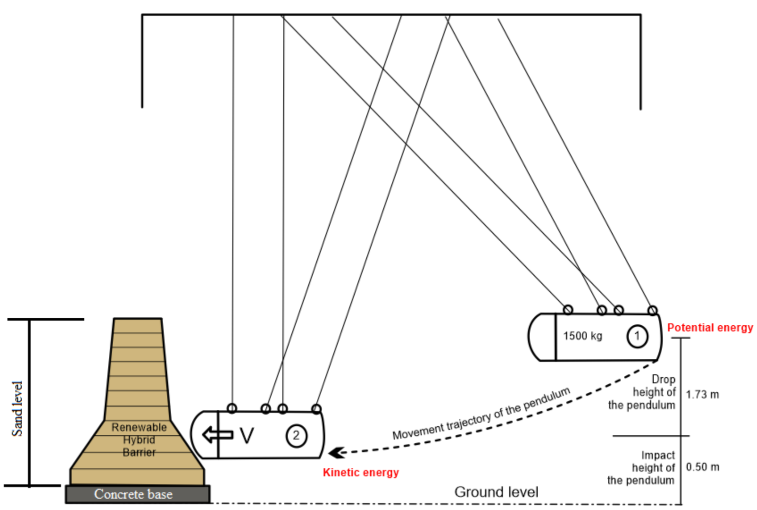

Fig. 4. Crash pendulum system (Yumrutaş *et al.* 2021)

The work of the pendulum system depends on the rule of preservation of energy. In position 1 the rammer has potential energy, and after release, it is converted to kinetic energy in position 2. Then it crashes into the barrier system with this energy. In this pendulum system, the rammer was lifted to 1.73 m height and generated 25.5 kJ energy for every test cycle (Yumrutaş *et al.* 2021).

RESEARCH METHODOLOGY

Research Process

There are various standards that can be used to assess the crash performance of vehicle barrier types, such as Road Restraint Systems standard EN 1317 (2010), Manual for Assessing Safety Hardware (MASH 2016), Recommended Procedures for the Safety Performance Evaluation of Highway Features (Ross *et al.* 1993), Roadside Design Guide (American Association of State Highway and Transportation Officials 2006), Standard test method for crash testing of vehicle security barriers (ASTM F2656 (2015), Impact test specifications for vehicle security barrier systems (BSI PAS 68 (2013), Vehicle security barriers (IWA 14 (2013), Road safety barrier systems (AS/NZS 3845 (1999), *etc.* In this study, EN 1317 (2010) Road Restraint Systems instructions were determined for optimization studies. The next step was the design of the RHBs and the design of the experimental crash pendulum system (Yumrutaş *et al.* 2021). The crash pendulum experiments provided verification data for virtual pendulum tests and a validation process for virtual full-scale crash tests was conducted. The last step was the optimization study to obtain the most suitable timber thickness resisting and absorbing the vehicle crash energy in terms of safety and structural performance, as well as cost. Figure 5 explains the research process step by step.

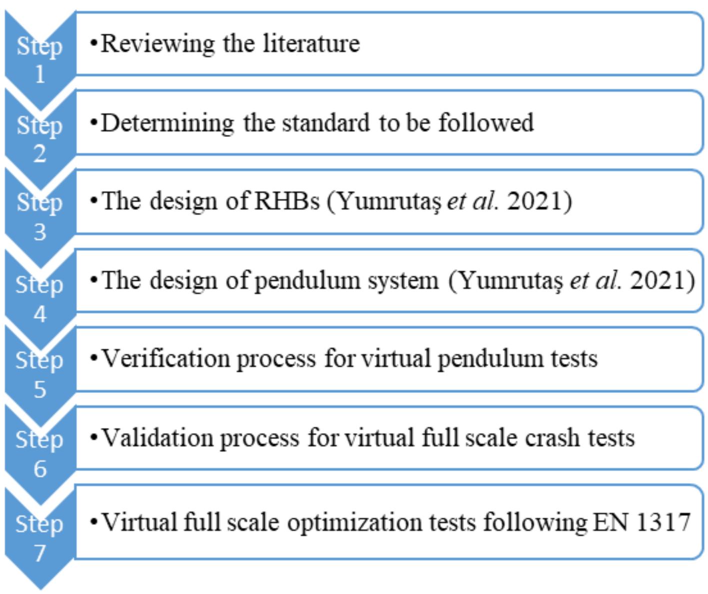

Fig. 5. Research process

Performance Metrics

The output assessment of the RHBs was controlled in accordance with EN 1317 (2010) Road Restraint Systems standard. This standard presents test techniques and impact test acceptance criteria that any barrier system needs to provide. The following performance criteria shall be met to restrain road vehicles (EN1317 (2010):

- The containment level;
- The acceleration severity index (ASI) and theoretical head impact velocity (THIV);
- The displacement as defined by the working width (W)

Road restraint systems shall meet the crash test requirements expressed in Table 1 and shall meet the requirements of Table 2 when tested following the impact test criteria presented in Table 1.

Table 1. Vehicle Impact Test Descriptions (EN1317 2010))

Test	Impact Speed (km/h)	Impact Angle (°)	Total Mass (kg)	Vehicle (Type)
TB 11	100	20	900	Car
TB 21	80	8	1300	Car
TB 22	80	15	1300	Car
TB 31	80	20	1500	Car
TB 32	110	20	1500	Car
TB 41	70	8	10000	Rigid HGV
TB 42	70	15	10000	Rigid HGV
TB 51	70	20	13000	Bus
TB 61	80	20	16000	Rigid HGV
TB 71	65	20	30000	Rigid HGV
TB 81	65	20	38000	Articulated HGV

Table 2. Containment Levels (EN1317 (2010))

Containment Levels		Acceptance Test
Low angle containment	T1	TB 21
	T2	TB 22
	T3	TB 41 and TB 21
Normal containment	N1	TB 31
	N2	TB 32 and TB 11
Higher containment	H1	TB 42 and TB 11
	L1	TB 42 and TB 32 and TB 11
	H2	TB 51 and TB 11
	L2	TB 51 and TB 32 and TB 11
	H3	TB 61 and TB 11
	L3	TB 61 and TB 32 and TB 11
Very high containment	H4a	TB 71 and TB 11
	H4b	TB 81 and TB 11
	L4a	TB 71 and TB 32 and TB 11
	L4b	TB 81 and TB 32 and TB 11

Because of their aesthetic view, there was a need for RHBs, particularly for scenic mountainous, touristic, and historical roadsides that have low traffic volume and are utilized predominantly by light vehicles. For this reason, TB 11 and TB 32 acceptance tests for N2 containment level were performed.

EN 1317 (2010) describes the ASI as a "measure of the severity of the motion for a person within a vehicle during an impact with a road restraint system" and the W as "the lateral distance between any part of the barrier on the not deformed traffic side and the maximum dynamic position of any part of the barrier." The THIV idea was created to assess occupant impact severity for vehicles involved in crashes with barrier systems. These are basic qualities to demonstrate the productivity of road restraint systems. A barrier's efficiency to keep the errant vehicle on the road platform decreases with the increased working width, so it should be within satisfactory cut-off points determined in standards. The ASI value is one of the signs of traveller security in the vehicle because of any impact with the barrier. The size of the speed of the THIV is a sign of the vehicle-to-restraint system impact severity. In this way, the ASI is determined by Eq. 1, and the THIV is determined by Eq. 2,

$$ASI = max\sqrt{\left(\frac{\bar{a}_x\,(t)}{12}\right)^2 + \left(\frac{\bar{a}_y\,(t)}{9}\right)^2 + \left(\frac{\bar{a}_z\,(t)}{10}\right)^2} \qquad (1)$$

where $\bar{a}_x$(t) is the maximum acceleration in x direction (m/s^2), $\bar{a}_y$(t) is the maximum acceleration in y direction (m/s^2), and $\bar{a}_z$(t) is the maximum acceleration in z direction (m/s^2). Equation 2 for theoretical head impact velocity (THIV, km/s) is as follows,

$$THIV = \sqrt{V_x^2\,(t) + V_y^2\,(t)} \qquad (2)$$

where $V_x\,(t)$ is the impact velocity of the head along x direction (km/s), and $V_y\,(t)$ is the impact velocity of the head along y direction (km/s).

The limit values of ASI and THIV safety parameters are given in Table 3. For assessing the safety performance of RHB, the following parameters were used.

Table 3. Impact Severity Levels (EN 1317 (2010))

Impact Severity Level	Index Values		
A	ASI ≤ 1.0	and	THIV ≤ 33 (km/h)
B	ASI ≤ 1.4		
C	ASI ≤ 1.9		

Two metrics were used to observe structural performance. These are W and exit box/exit angle (α). Working width limits in EN 1317 (2010) are given in Table 4.

Table 4. Working Width Levels (EN 1317 (2010)

Classes of Working Width Levels	Levels of Working Width (m)
W1	W ≤ 0.6
W2	W ≤ 0.8
W3	W ≤ 1.0
W4	W ≤ 1.3
W5	W ≤ 1.7
W6	W ≤ 2.1
W7	W ≤ 2.5
W8	W ≤ 3.5

Exit box criteria shall be considered in virtual full-scale tests. The errant vehicle behavior after any accident shall be exceptionally critical and essential. An effective guardrail is supposed to put back the errant vehicle to pass over or supposed to redirect to the road platform at a small angle. In this way, a second probable car crash because of the errant vehicle that passes over the guardrail to the opposite lane or redirects back to the center of the initial traffic lanes can be prevented. The exit box can be determined with A and B values as shown in Table 5 and as illustrated in Fig. 6.

Table 5. Distance for Exit Box Criterion (EN 1317 (2010))

Vehicle Type	A (m)	B (m)
Passenger car	2.2	10
Other vehicles	4.4	20

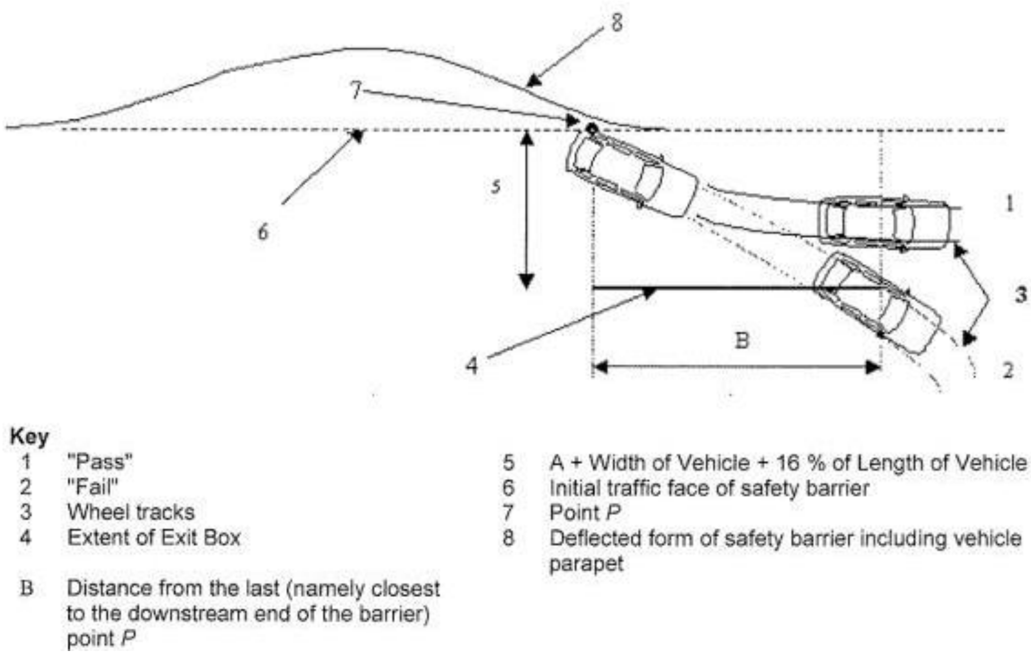

Fig. 6. The visual explanation of exit box concept (EN 1317 (2010))

Additionally, failure analysis needs to be observed by visual inspection. Finally, relative absolute error (RAE) metric was performed to verify and correctly control of the simulation results with the pendulum test results, taking into account Eq. 3,

$$RAE = \left|\frac{y_p - y_s}{y_p}\right| \tag{3}$$

where y_p and y_s are the pendulum result and the simulation result, respectively.

In this study, virtual tests were employed by experimentally verified data considering the performance metrics of related standards.

VIRTUAL TESTS

Roadside barriers (bollard systems) must undergo full-scale crash tests that have high costs and long processes to test their safety and structural performance. However, the performance of roadside barriers (bollard systems) can be simulated by finite element (FE) analyses more quickly, reliably, and economically than real tests (Apak 2019). The modelling and simulation of traffic accidents improved considerably, allowing researchers to model and analyze the performance of roadside barriers. Therefore, FE analyses have become an important tool to analyze roadside barriers with cost-effective solutions (Atahan and Cansiz 2005; Atahan 2006, 2010; Atahan *et al.* 2014). In this regard, LS-DYNA finite element simulation software that is used primarily in dynamic crashworthiness analysis was effectively applied in many studies (Wright and Ray 1996; Eskandarian *et al*. 1997; Ray 1997; Plaxico *et al.* 1998; Uddin and Hackett 1999; Atahan 2002, 2006; Tiso *et al.* 2002; Kirkpatrick *et al.* 2003; Bligh *et al.* 2004; Reid 2004; Whitworth *et al.* 2004; Wu and Thomson 2004; Griškevičius *et al.* 2007; Vesenjak *et al.* 2007; Tabacu and Pandrea 2008; Štych 2010; Ferdous *et al.* 2011; Amato *et al.* 2013; Borovinšek *et al*. 2013; Neuenhaus *et al*. 2013; Mirdamadi 2014; Mojdeh 2015; Teng *et al.* 2016; Yin *et al.* 2016; Soltani *et al.* 2017; Tabiei and Wu 2000, 2020; Baranowski and Damaziak 2021; Apak *et al.* 2022) and also will be applied in this study. Pendulum crash tests have also been conducted widely in the literature to verify and validate the virtual simulation tests (Gatchell and Michie 1974; Bank and Gentry 2001; Frp *et al.* 2001; Atahan *et al.* 2002; Mitchell *et al.* 2006; Atahan and Sevim 2008; Faller *et al.* 2009; Marzougui 2009; Ucar and Cengiz 2012; Kuilen 2019; Luo *et al.* 2020).

Verification Process of the Virtual Pendulum Test System

The experimental pendulum tests data used for verification was provided from the study by Yumrutaş *et al.* (2021). The wooden materials (timbers) of 2 and 4 cm in thickness were evaluated by crash pendulum tests. The results were employed for the verification process of virtual pendulum tests. Figure 7 shows the pendulum system and the FE models that were used for verification.

A

B

Fig. 7. (A) Pendulum system and (B) its FE model

The pendulum crash tests and virtual full-scale tests for TB 11 and TB 32 acceptance criteria were conducted considering the experiment matrix in Table 6.

Table 6. Experiment Matrix

	Pendulum		TB 11 Tests					TB 32 Tests				
Timber Thickness (cm)	2	4	2	4	6	8	10	2	4	6	8	10
Real-time Pendulum Tests	+	+	-	-	-	-	-	-	-	-	-	-
Virtual Full-Scale Tests	+	+	+	+	+	+	+	+	+	+	+	+
(+) applied, (-) not applied												

Validation Process of Virtual Full-scale Crash Tests

Virtual full-scale tests were completed as TB 11 and TB 32 acceptance tests for N2 containment level using Ls-Dyna (Livermore Software Technology, Version R12.1.0, Livermore, CA, USA) simulation software. The sufficient barrier length was determined as 25 m to be able to observe the collaborative crash-resistant behavior of the RHBs and to observe the trajectory of the car on the road platform after any accident.

In this study, considering the TB 11 and TB 32 acceptance tests for N2 containment level, 900 kg, and 1500 kg in weight passenger car model that was validated by National Highway Traffic Safety Administration (NHTSA), was utilized as presented in Fig. 8 (NHTSA 2008). The original model was 900 kg, and the 1500 kg vehicle was adjusted to 1500 kg with the help of defined mass points (MassD) in the original model.

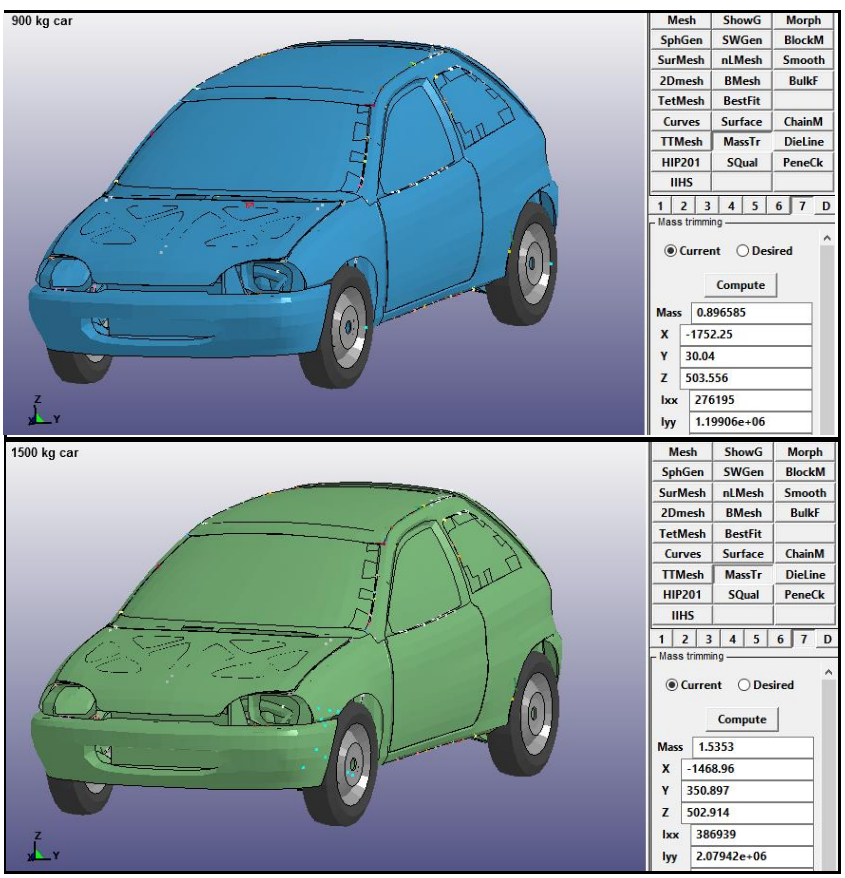

Fig. 8. The virtual passenger car validated by NHTSA 900 and 1500 kg in weight (NHTSA 2008)

The first grade (first quality) fir timbers were used. Consistent with the experimental data, input parameters of LS-DYNA were specified for the timber elements as follows. The moisture content of the timbers are % 8, bending strength is 72,92 N/mm^2, modulus of elasticity is 9691,27 N/mm^2, tensile strength parallel to fibers is 51.84 N/mm^2, compressive strength parallel to fibers is 51.29 N/mm^2, air dry density is 0.57 gr/cm^3.

The exit box was determined as given in Table 7 and by utilizing the dimensions of the validated vehicle model, which was 3.75 m in length and 1.56 m in width (Fig. 9). According to the exit box, the maximum exit angle was calculated as approximately 24°, assuming that the crashed vehicle leaves within the short side of the exit box.

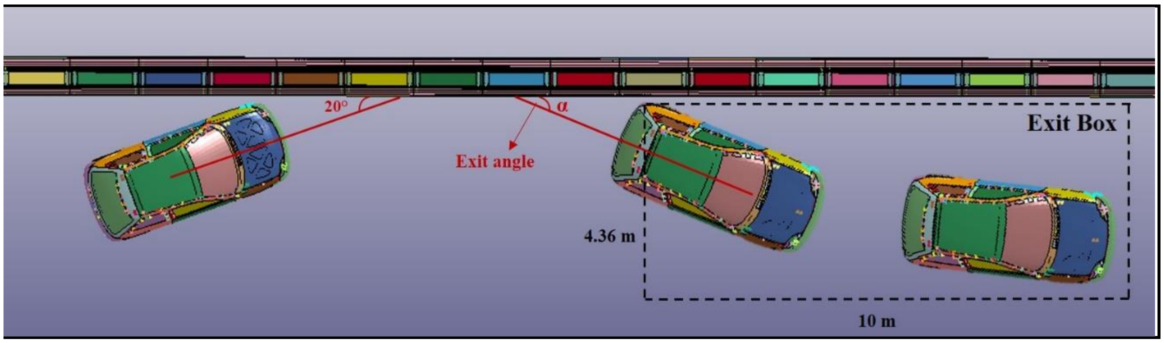

Fig. 9. The exit box boundaries for validated passenger car

RESULTS

The system had enough structural capacity to withstand the impact of the test vehicle and absorb the impact energy. In addition, the system also was able to contain and redirect the vehicle to the desired exit box boundaries. However, this study aimed to find the optimum timber thickness to attain the safest and the most cost-effective solution.

Real-Time/Virtual Pendulum Test Results

The real-time pendulum test results (Yumrutaş *et al.* 2021) were checked against the virtual pendulum model results for accurate verification.

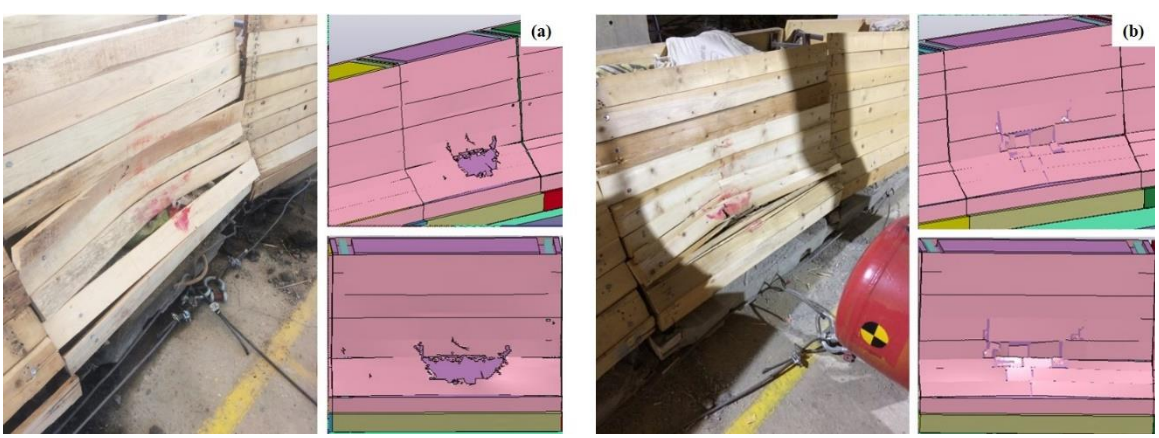

Fig. 10. The visual deformation results of real-time and virtual pendulum tests: a) 2 cm timber in thickness, b) 4 cm timber in thickness

In Fig. 10, the visual results obtained from the real-time pendulum test were checked against the virtual pendulum results and similar deformations occurred on the traffic face and no deformation occurred on the back face of the RHBs.

Through employing deceleration and *W* values, a quantitative verification was also conducted in addition to this qualitative verification. The RAE evaluation in Table 7 exhibits acceptable values for accurate verification. Therefore, the virtual results revealed consistency with the real-time pendulum test results and within the acceptable limits according to the standard, EN 16303 (2020). This means that virtual models verified with the help of results from the real-time pendulum tests can be used for the validation process of full-scale virtual crash models.

Table 7. Comparison of Real Time and Virtual Pendulum Test Results

Timber Thickness (cm)	Deceleration (m/s^2)		RAE (%)	*W* (m)		RAE (%)
	Pendulum	Simulation		Pendulum	Simulation	
2	5.80	6.16	**5.84**	0.87	0.93	**6.45**
4	5.36	5.62	**4.63**	1.08	1.14	**5.26**

The consistency of the real-time pendulum tests with the virtual pendulum tests based on timing is depicted in Fig. 11.

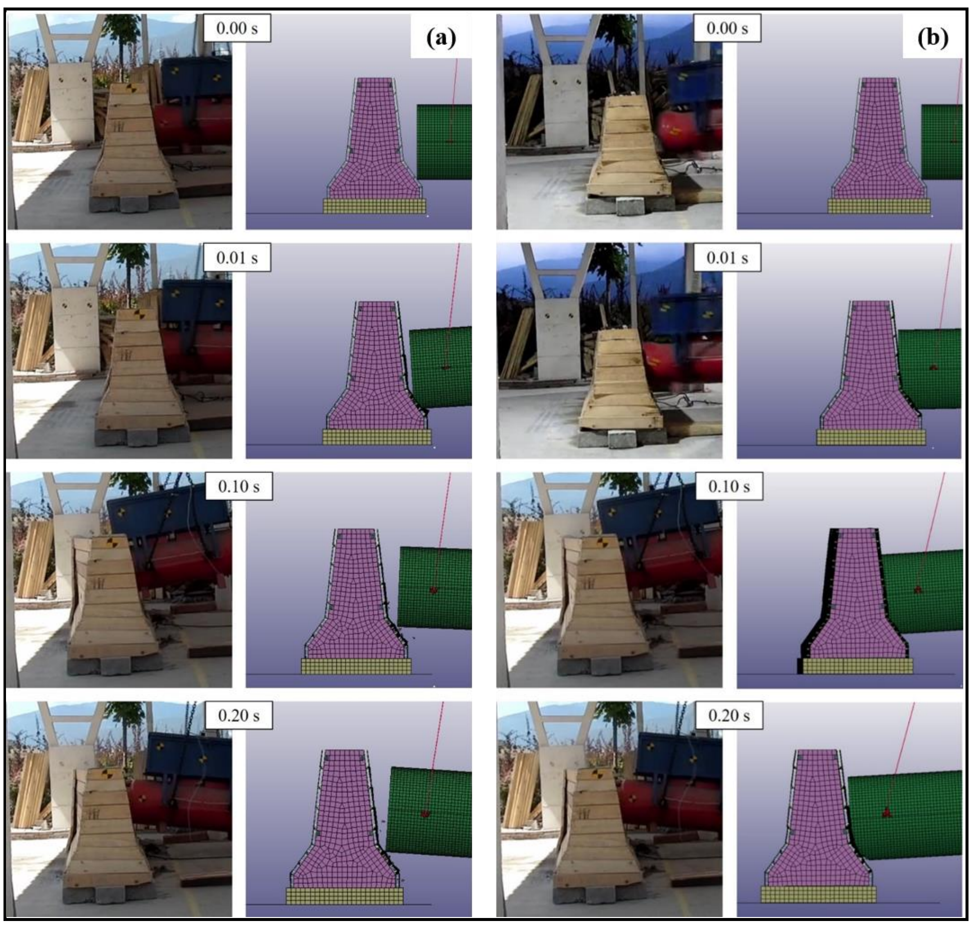

Fig. 11. The consistency of real-time and virtual pendulum tests results depending on the timing: (a) 2 cm in timber thickness, (b) 4 cm in timber thickness

After verification of the virtual pendulum model, the validation process of the full-scale crash for TB 11 and TB 32 acceptance tests was conducted.

Safety Performance of RHBs from Virtual Full-scale TB 11 Tests Results

The test in which a barrier safety is measured in the EN 1317 (2010) standard is TB 11. With this test, safety parameters, such as ASI and THIV, are measured. Therefore, in this study, the ASI and THIV values obtained for different timber thicknesses as a result of the TB 11 tests performed for RHB are presented in Table 8. Accordingly, ASI and THIV values increased as the wood thickness increased.

Table 8. Quantitative Performance Values for Virtual Full-scale TB 11 Test

Timber Thickness (cm)	ASI	THIV (km/h)
2	1.03 (B)	28
4	1.12 (B)	30
6	1.24 (B)	30
8	1.35 (B)	31
10	1.45 (C)	33

In addition, the ASI comparison for all timber thicknesses is given in Fig. 12. The ASI values demonstrated that RHBs, which were produced with 2, 4, 6, and 8 cm timber in thicknesses, are safer with B class ASI value than the ones which were produced with 10 cm timber in thickness with C class ASI value. However, all of them met the required performance criteria specified in EN 1317 (2010). It was also observed (Table 8) that THIV values were lower than the limit value given in EN 1317 (2010).

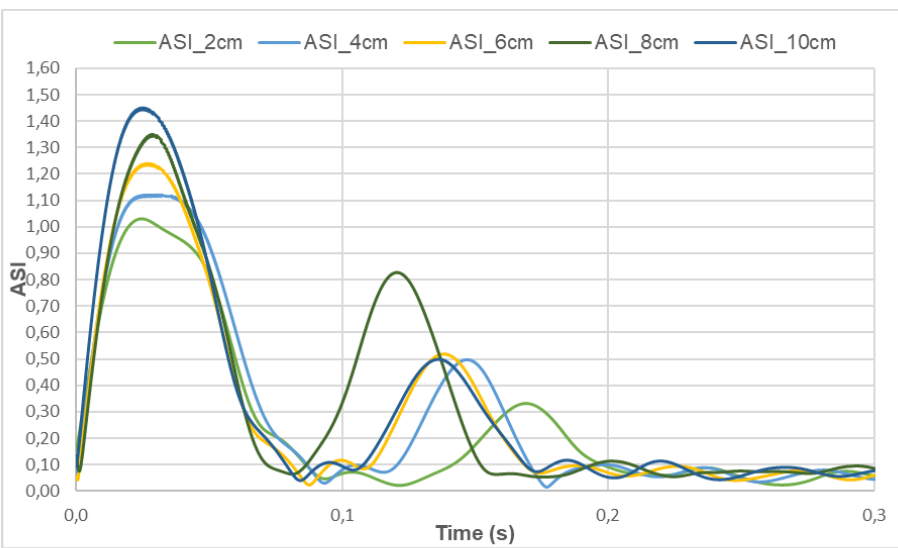

Fig. 12. Comparison of ASI values of RHBs with different timber thicknesses

In addition to the quantitative comparisons given above, a visual comparison of RHBs of different timber thicknesses is depicted in Fig. 13. Results show that the heights of the vehicles after crashing were different. The higher the vehicles and the greater the displacement, the lower the ASI value will be due to this flexibility. It was understood that as the timber thickness increased, the ASI values increased undesirably due to the increase in the barrier mass and its more rigid behavior.

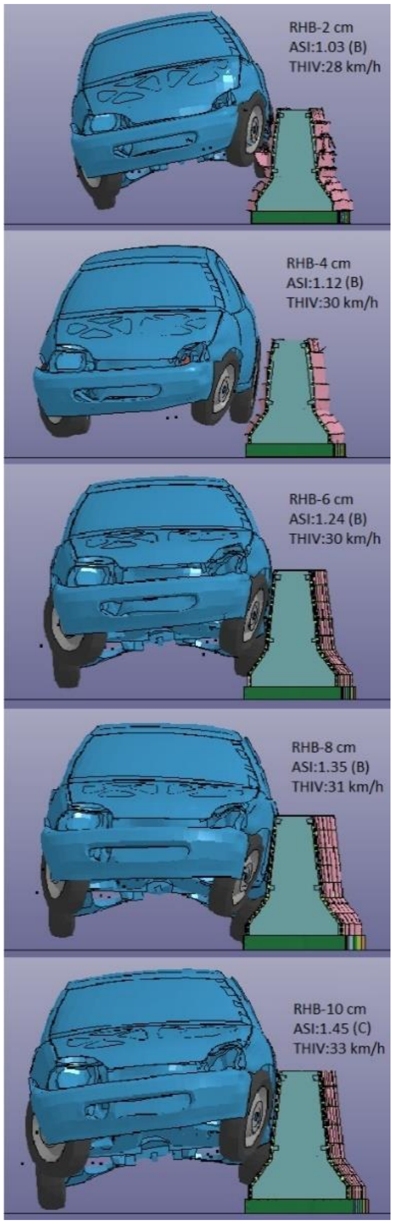

Fig. 13. A visual comparison of ASI and THIV values of RHBs with TB 11 tests

Structural Performance of RHBs from Virtual Full-scale TB 32 Tests Results

For N2 level in the EN 1317 (2010) standard, the test in which the barrier structural performance is determined is TB 32. The barrier's *W* and *α* values are the criteria that determine the barrier's structural performance. The results obtained in the test for barriers with different timber thicknesses are presented in Table 9. The table indicated that, as the timber thicknesses increased, the *W* decreased due to the increase in the barrier mass. The exit angle values remain almost the same for all timber thicknesses, much smaller than the maximum exit angle of 24° calculated for the specified exit box.

Table 9. Quantitative Performance Values for Virtual Full-scale TB 32 Test

Timber Thickness (cm)	*W* (m)	Exit Angle-α (°)	In Exit Box (yes/no)
2	0.94 (W3)	2	yes
4	0.90 (W3)	4	yes
6	0.87 (W3)	4	yes
8	0.83 (W3)	4	yes
10	0.80 (W3)	3	yes

In addition to the quantitative performance (W, α) values, qualitative performance results were obtained and are presented in Fig. 14.

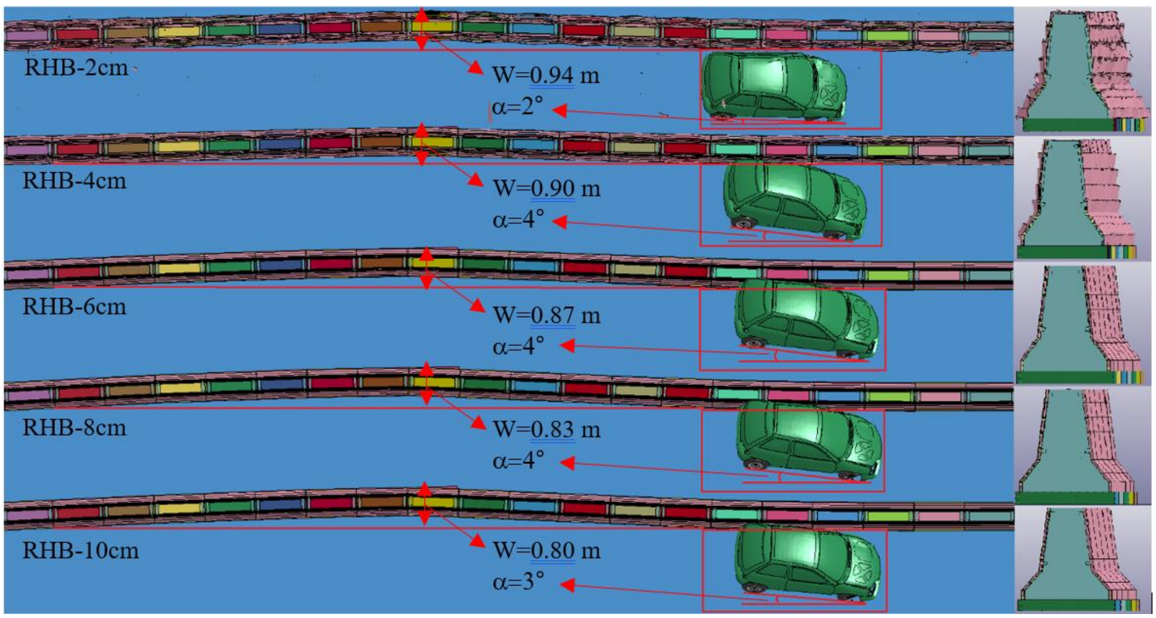

Fig. 14. Qualitative comparison of the TB 32 with W and α values

When the results for TB 32 tests were examined, the RHBs for all timber thicknesses were similar but exhibited different deflections during the crash of the vehicle and provided the same *W* value as W3 class. Thereafter, the vehicle stopped and stayed within the exit box boundaries for all RHBs with different timber thicknesses. These results proved the success of all timber thicknesses to contain and redirect the errant vehicles in the desired trajectories, which is nearly parallel to the barrier. Results also proved that the timber thicknesses did not allow vehicles to pass over the barriers.

Failure Analysis of RHBs from TB 11 and TB 32 Tests Results

Each of the RHBs was produced 1.25 m in length and the sufficient total barrier length was determined as 25 m in virtual tests. This allowed observation of the collaborative crash-resistant behavior of the RHBs. The virtual failure analysis results of TB 11 and TB 32 tests are presented in Table 10. For both tests, deformation (cracks) occurred only at timber thicknesses of 2 and 4 cm. However, no disruption of integrity in the whole barrier system for all thicknesses was observed. The deformations on the surface of each RHBs are indicated in Fig. 15.

Table 10. Failure Analysis of RHB

Timber Thickness (cm)	Number of Damaged Timbers	
	TB11	TB32
2	6	16
4	4	6
6	0	0
8	0	0
10	0	0

As can be seen in Fig. 15, deformations occurred more prominently in the TB 32 test due to the vehicle mass and speed, but as in the TB 11 test, deformations occurred only in RHBs with 2 and 4 cm timber thicknesses. As a result, it was understood that the critical thickness of the timber in terms of deformation resistance was 6 cm.

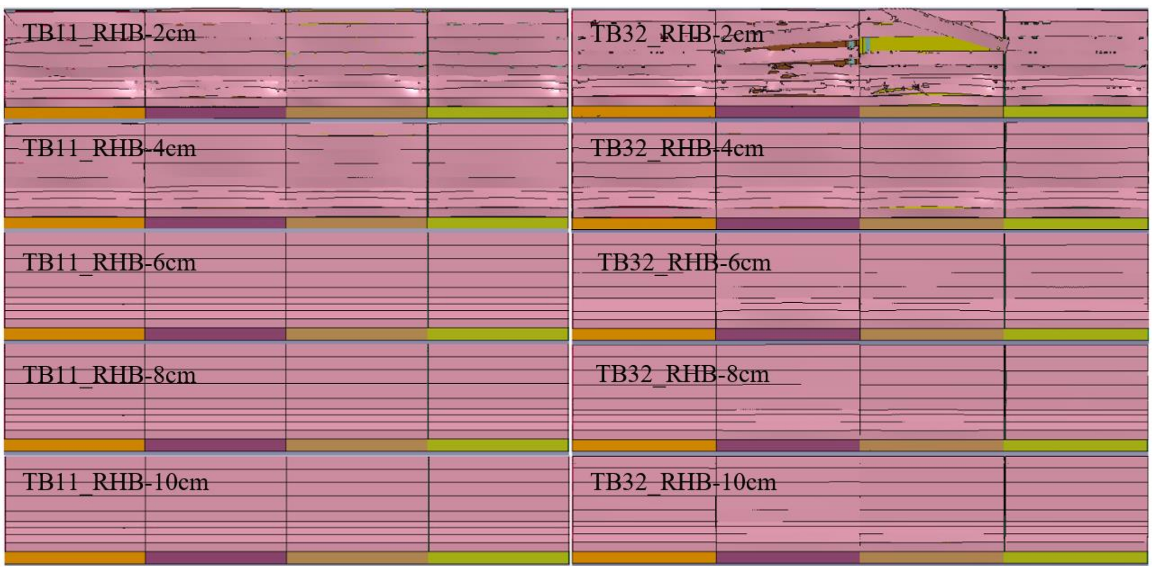

Fig. 15. TB 11 and TB 32 test performance of the RHB and timber failure

CONCLUSIONS

In this study, the safety performance (ASI, THIV), structural performance (working width *W*, and exit angle α), and failure analysis (visual deformation) of a newly developed F-shape type renewable hybrid barrier (RHB) system at different timber thicknesses were tested *via* pendulum test and finite element (FE) models. The FE models were calibrated and validated based on pendulum test results, and then the most suitable timber thickness in terms of safety and structural performance was tested with the help of FE analyses. As a result of the study, the following outputs were achieved:

1. As a result of TB 11 tests, the safest timber thickness numerically was determined as 2 cm. As the timber thickness increased, the safety parameters, such as ASI and THIV, increased, thus decreasing the barrier safety. The ASI value falls within the same range (B) for RHBs up to 8 cm timber thickness. The THIV value meets the EN 1317 (2010) requirements in all timber thicknesses.

2. As a result of TB 32 tests, the *W* value of all timber thicknesses remained within the W3 level of EN 1317 (2010). This showed that the thickness of the timber has little effect on the *W* value. At the same time, the small α values confirmed that the crashing vehicle left the barrier in a way that would not pose a traffic hazard and that it met the EN 1317 (2010) requirements.
3. As a result of TB 11 and TB 32 tests, deformations were observed in RHBs only 2 and 4 cm in thickness. In the impact, only the timbers were damaged, depending on the thickness; however any damage was not possible for the sand material. It is obvious that the main material affecting the performance of RHBs is sand, and the cost of sand is low, thus diminishing the total barrier cost.
4. When the results are examined, it is understood that the timber thicknesses in the RHBs have little effect on the ASI and *W* values. In the light of the ASI, THIV, *W*, α, and deformation values obtained as a result of the TB 11 and TB 32 tests, the most suitable RHB timber thickness should be around 6 cm; however, the most suitable thickness will be 2 cm in terms of safety and cost without considering the deformation after any collision.
5. In this study, dry crushed stone sand, 0 to 5 mm in dimensions, was used. However, the effect of physical parameters of sand (dimensions, shape, density, and water content) on crash performance parameters should be researched in future studies.
6. It is highly recommended to consider more research in this field with various shapes and various waste materials as filling materials to improve the severity levels of RHBs.
7. Wooden barrier types in the literature are not widely used in practice due to high costs. In the production of renewable hybrid barriers, the cost was reduced due to the use of sand in addition to wood, and it is supposed to be much more applicable than its similar alternatives.
8. Enriching the usage areas of wood and wood-based materials instead of materials with higher greenhouse gas emissions in their production will contribute to reducing global warming.
9. In future studies, different types of wooden materials can be employed instead of fir timber and additionally the effect of heat treatment and impregnation process on the performance and thickness can be observed.

This research contributes to developing novel barrier types as an alternative to traditional steel and concrete materials as an aesthetic and environmentally friendly solution.

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