

Collision Safety and Life-Cycle Carbon Emission Assessment of GFRP Corrugated Beam Guardrails

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Abstract. To evaluate the feasibility of glass fiber-reinforced polymer (GFRP) corrugated beam guardrails for low-carbon road safety facilities, this study compares GFRP and Q235 steel Class A W-beam guardrails in terms of collision safety and life-cycle carbon emissions. Vehicle–guardrail finite element models were established, and impact conditions of 5°, 10°, and 20° were considered. A life-cycle carbon emission assessment was conducted using 1 km of guardrail over a 50-year service period as the functional unit. The results show that the GFRP guardrail can contain and redirect the vehicle under all impact conditions. Under the standard 20° impact condition, its maximum lateral dynamic deflection is 660 mm and the vehicle exit angle is 10.7°, satisfying the selected Class A evaluation indicators. Compared with the Q235 steel guardrail, the peak resultant acceleration decreases from $178.5 \text{ m}\cdot\text{s}^{-2}$ to $142.3 \text{ m}\cdot\text{s}^{-2}$, a reduction of 20.3%. The life-cycle carbon emissions of the GFRP guardrail are $66,000 \text{ kg CO}_2\text{-eq}\cdot\text{km}^{-1}$, which is 34.5% lower than those of the Q235 steel guardrail. Sensitivity analysis indicates that the GFRP material emission factor and cumulative maintenance replacement ratio are the dominant parameters.

Keywords: GFRP guardrail; corrugated beam guardrail; collision safety; finite element simulation; life-cycle assessment; carbon emissions; low-carbon road safety facilities.

1. Introduction

Roadside guardrails are essential highway safety facilities for containing, cushioning, and redirecting vehicles that leave the roadway. Q235 steel corrugated beam guardrails are widely used because of their mature design and stable protection performance. However, steel production generates considerable carbon emissions, and corrosion during service increases maintenance and replacement demand^[1]. With the development of low-carbon transportation infrastructure, guardrail materials should be evaluated not only for collision safety but also for life-cycle environmental impact.

Glass fiber-reinforced polymer (GFRP) composites offer low density, corrosion resistance, design flexibility, and favorable energy absorption capacity. Compared with steel, GFRP can reduce component weight, transportation load, and anti-corrosion maintenance demand. During impact, GFRP structures may dissipate energy through matrix cracking, fiber fracture, and delamination, which can improve cushioning performance. These characteristics make GFRP a promising material for corrugated beam guardrails^[2].

Existing studies have examined FRP impact behavior, composite guardrail optimization, and vehicle–guardrail collision simulations. However, the containment, cushioning, and redirection performance of GFRP corrugated beam guardrails under standard vehicle impact conditions remain insufficiently investigated. Quantitative comparisons of life-cycle carbon emissions between GFRP and steel guardrails are also limited. To address these gaps, this study establishes vehicle–guardrail finite element models for GFRP and Q235 steel Class A W-beam guardrails. Collision safety is evaluated under different impact angles, and life-cycle carbon emissions are compared using 1 km of guardrail over a 50-year assessment period as the functional unit^[3].

2. Guardrail Design and Finite Element Modeling

2.1 Structural Configuration and Material Parameters of the Guardrail

The Class A two-wave W-beam guardrail used on highways was selected as the research object. Models of both GFRP and Q235 steel guardrails were developed with the same structural configuration and protection level. The guardrail system consisted of W-beams, spacer blocks, posts, and connectors. For the GFRP guardrail, the corrugated beam material was replaced by GFRP while the main geometric configuration remained unchanged, as shown in Fig. 1.

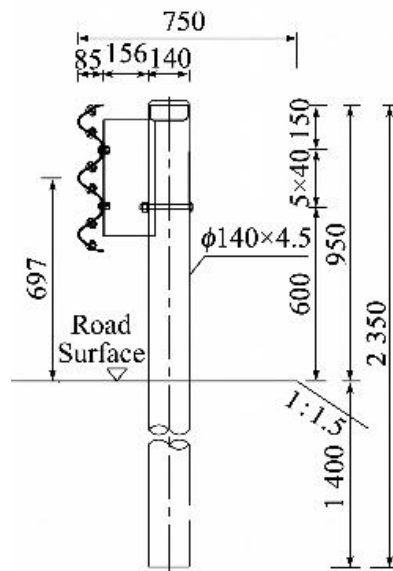


Fig. 1 Structural configuration of the Class A W-beam guardrail

In the finite element model, the GFRP material was described using the MAT_58 composite damage model^[4], and the Hashin failure criterion was used to determine damage initiation^[5]. This model can represent the anisotropic response, stiffness degradation, and progressive damage behavior of GFRP under impact loading. The material parameters were determined with reference to the commercial certification data of Strongwell EXTREN® pultruded structural profiles^[6]. The main parameters are listed in Table 1.

Table 1. Material properties of GFRP

Parameter	Value
Longitudinal Young's modulus / MPa	19,300
Transverse Young's modulus / MPa	9,000
In-plane shear modulus / MPa	5,000
Longitudinal tensile strength / MPa	250
Longitudinal compressive strength / MPa	220
In-plane shear strength / MPa	73.1
Density / g·cm ⁻³	1.82
Poisson's ratio	0.33
Thickness / mm	3.3

As shown in Table 1, the density of GFRP is significantly lower than that of steel, while its elastic modulus is also relatively lower. Therefore, the GFRP guardrail may exhibit larger lateral deformation during vehicle impact. Whether this deformation is acceptable should be comprehensively evaluated in terms of containment, cushioning, and redirection performance.

2.2 Finite Element Modeling of Vehicle–Guardrail Collision

A nonlinear explicit dynamic model was established to simulate the vehicle–guardrail collision. According to the Class A guardrail test condition specified in JTG B05-01—2013, a 1.5 t passenger car impacted the guardrail at an initial speed of 100 km/h. Three impact angles of 5° , 10° , and 20° were considered, with 20° representing the standard impact condition. The vehicle model was based on the validated 1996 Dodge Neon finite element model released by the National Crash Analysis Center^[7].

The guardrail model included the W-beam, spacer block, post, and connectors. The model was preprocessed in HyperMesh, and the main components were discretized using Belytschko–Tsay shell elements with a typical mesh size of 20 mm. Bolted joints were represented by connection constraints. Automatic surface-to-surface contact was defined between the vehicle and the guardrail, and single-surface contact was used for possible self-contact of structural components^[8]. The vehicle impacted the guardrail at approximately one-third of the standard section length, as shown in Fig. 2.

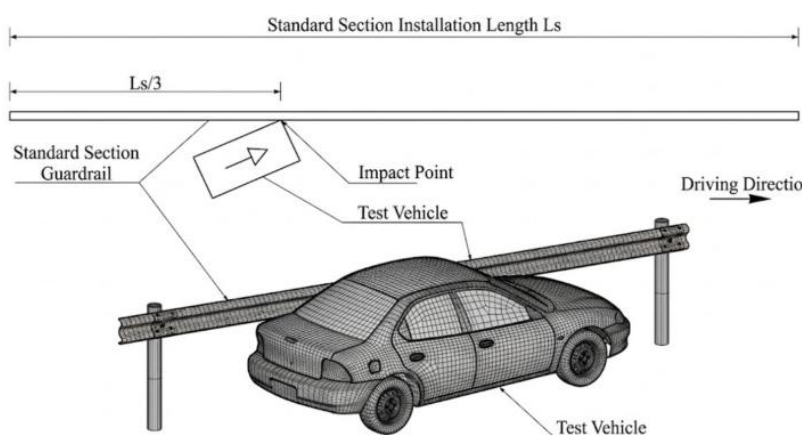


Fig. 2 Finite element model of vehicle–guardrail collision

The maximum lateral dynamic deflection, peak resultant acceleration at the vehicle center of gravity, vehicle exit angle, and energy absorption of major components were extracted for safety evaluation. To verify numerical stability, the energy balance under the standard 20° impact condition was examined, as shown in Fig. 3.

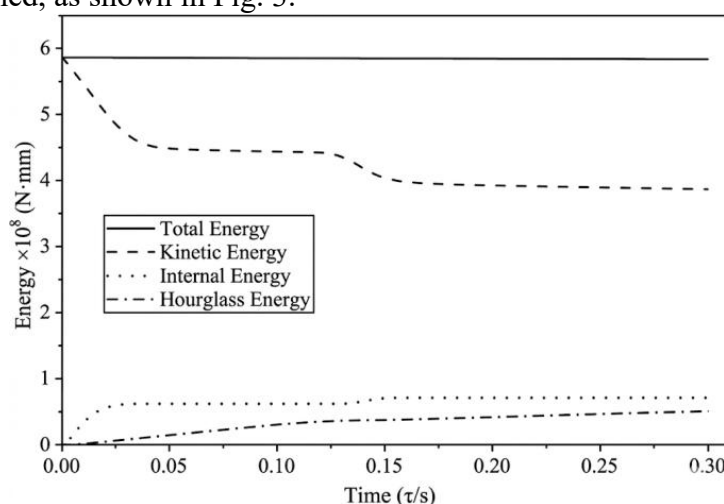


Fig. 3 Energy balance verification of the vehicle–guardrail coupled system

During the collision, the initial kinetic energy was gradually converted into internal energy, while the total energy remained stable. The maximum hourglass energy accounted for approximately 4.8% of the total energy, indicating that the mesh, contact algorithm, and time-step

control were reasonably configured. Therefore, the finite element model was considered suitable for comparing the collision safety performance of GFRP and Q235 steel guardrails.

2.3 Evaluation Indicators for Collision Safety

According to the Safety Performance Evaluation Standard for Highway Guardrails, this study selects the maximum lateral dynamic deflection, the peak resultant acceleration at the vehicle's center of gravity, and the vehicle exit angle as evaluation indicators to assess the containment, cushioning, and redirection performance of the guardrail, respectively. The vehicle should not penetrate, override, or straddle the guardrail. For the 20° impact condition, the vehicle exit angle is recommended to be less than 60% of the impact angle, namely 12°.

3. Methodology for Life-Cycle Carbon Emission Assessment

3.1 Functional Unit, System Boundary, and Inventory Data

To compare the life-cycle carbon emissions of GFRP and Q235 steel W-beam guardrails under the same protection function, the functional unit was defined as 1 km of Class A W-beam guardrail over a 50-year assessment period^[9].

The system boundary covered five stages: raw material production, component manufacturing, transportation and construction, service and maintenance, and end-of-life disposal. The inventory data included the equivalent material consumption of the compared guardrail systems, transportation distance, installation energy consumption, maintenance interval, cumulative replacement ratio, and recycling rate. The guardrail length, assessment period, and material consumption were determined from the functional unit, structural dimensions, and material density^[10]. Other parameters were selected with reference to LCA studies on road safety facilities and comparable maintenance scenarios. The inventory data are listed in Table 2.

Table 2. Life-cycle inventory data

Parameter	GFRP guardrail	Q235 steel guardrail
Guardrail length, L / km	1	1
Assessment period, T / year	50	50
Mass per unit length, m_i / (kg/m)	13.2	28.0
Total material consumption, M / kg	13,200	28,000
Glass fiber mass fraction, R_f / %	60	—
Resin mass fraction, R_r / %	40	—
Galvanized coating mass, M_z / kg	—	840
Transportation distance, D / km	300	300
Installation energy consumption, E_c / kg fuel	420	550
Maintenance interval, t_m / year	10	5
Cumulative maintenance replacement ratio, R_m / %	5.0	30.0
Maintenance material consumption, M_m / kg	660	8,400
Material recycling rate, r_e / %	10	85
Disposal method	Disposal or resource recovery	Steel recycling

As shown in Table 2, the GFRP guardrail has lower mass per unit length, a longer maintenance interval, and a lower cumulative replacement ratio than the Q235 steel guardrail, but its recycling rate is also lower. These differences provide the basis for the subsequent life-cycle carbon emission calculation.

3.2 Carbon Emission Calculation and Sensitivity Analysis

The emission factor method is adopted in this study to quantify the life-cycle carbon emissions of GFRP W-beam guardrails and Q235 steel guardrails. The total life-cycle carbon emissions are calculated as the sum of emissions generated during five stages, namely raw material production, component manufacturing, transportation and construction, service and maintenance, and end-of-life disposal. The calculation formula is given as follows:

$$C_{\text{total}} = C_m + C_p + C_t + C_u + C_e \quad (1)$$

where C_{total} denotes the total life-cycle carbon emissions of the guardrail. C_m , C_p , C_t , C_u , and C_e denote the carbon emissions associated with the raw material production, component manufacturing, transportation and construction, service and maintenance, and end-of-life disposal stages, respectively. The unit of each term is $\text{kg CO}_2\text{-eq}\cdot\text{km}^{-1}$. The carbon emissions of each stage are calculated as the product of activity data and the corresponding emission factor:

$$C_j = \sum_i A_{ij} \times EF_{ij} \quad (2)$$

where A_{ij} is the activity data, including material consumption, transportation workload, fuel consumption, maintenance material consumption, or end-of-life material quantity, and EF_{ij} is the corresponding emission factor.

The emission factors were selected from life-cycle inventory reports, environmental product declarations, and published LCA studies^[11]. The factors for steel, zinc coating, GFRP materials, transportation, construction fuel, maintenance, and end-of-life treatment are listed in Table 3.

Table 3. Main Carbon Emission Factors

Emission object or process	Value	Unit
GFRP composite material	3.60	$\text{kg CO}_2\text{-eq}\cdot\text{kg}^{-1}$
Q235 steel	1.86	$\text{kg CO}_2\text{-eq}\cdot\text{kg}^{-1}$
Galvanized coating material	3.69	$\text{kg CO}_2\text{-eq}\cdot\text{kg}^{-1}$
GFRP molding and processing	0.87	$\text{kg CO}_2\text{-eq}\cdot\text{kg}^{-1}$
Steel component processing and hot-dip galvanizing	0.51	$\text{kg CO}_2\text{-eq}\cdot\text{kg}^{-1}$
Road transportation	0.25	$\text{kg CO}_2\text{-eq}\cdot\text{t}^{-1}\cdot\text{km}^{-1}$
Construction fuel	3.17	$\text{kg CO}_2\text{-eq}\cdot\text{kg}^{-1}$
GFRP maintenance composite factor	6.06	$\text{kg CO}_2\text{-eq}\cdot\text{kg}^{-1}$
Q235 steel guardrail maintenance composite factor	3.75	$\text{kg CO}_2\text{-eq}\cdot\text{kg}^{-1}$
GFRP end-of-life disposal	0.049	$\text{kg CO}_2\text{-eq}\cdot\text{kg}^{-1}$
Net credit for steel recycling	-0.17	$\text{kg CO}_2\text{-eq}\cdot\text{kg}^{-1}$

As shown in Table 3, the stages of raw material production, component manufacturing, transportation and construction, service and maintenance, and end-of-life disposal are all included in the carbon emission calculation. Among these factors, the net credit for steel recycling is assigned a negative value to represent the emission reduction benefit generated by steel recycling at the end-of-life stage. To compare the low-carbon performance of the GFRP guardrail relative to the Q235 steel guardrail, the life-cycle carbon emission reduction rate is calculated as follows:

$$R_{\text{sen}} = \frac{C_{\text{steel, sen}} - C_{\text{GFRP, sen}}}{C_{\text{steel, sen}}} \times 100\% \quad (3)$$

where R_{sen} denotes the life-cycle carbon emission reduction rate of the GFRP guardrail relative to the Q235 steel guardrail after the perturbation of key parameters. $C_{\text{steel, sen}}$ and $C_{\text{GFRP, sen}}$ denote the total life-cycle carbon emissions of the Q235 steel guardrail and the GFRP guardrail under the sensitivity analysis scenario, respectively, with the unit of $\text{kg CO}_2\text{-eq}\cdot\text{km}^{-1}$. To examine the stability of the life-cycle carbon emission assessment results, this study selects the carbon emission factor of GFRP materials, transportation distance, service-stage maintenance replacement rate, and material recycling rate for $\pm 20\%$ perturbation analysis^[12]. The total life-cycle carbon emissions and

emission reduction rates of the two types of guardrails are then recalculated. For the Q235 steel guardrail, the upper limit of the perturbed steel recycling rate does not exceed 100%.

4. Results and Discussion

4.1 Collision Safety Performance Analysis

To evaluate the safety performance of the GFRP W-beam guardrail, the collision responses of the GFRP and Q235 steel guardrails were compared under impact angles of 5°, 10°, and 20°. The maximum lateral dynamic deflection, peak resultant acceleration at the vehicle center of gravity, and vehicle exit angle were selected to evaluate containment, cushioning, and redirection performance, respectively. The results are listed in Table 4.

Table 4. Collision Safety Evaluation Results

Evaluation indicator	Guardrail type	5°	10°	20°
Maximum lateral dynamic deflection / mm	Q235 steel guardrail	380	510	620
Maximum lateral dynamic deflection / mm	GFRP guardrail	460	620	660
Peak resultant acceleration / (m s^{-2})	Q235 steel guardrail	68.2	115.4	178.5
Peak resultant acceleration / (m s^{-2})	GFRP guardrail	55.6	92.1	142.3
Vehicle exit angle / °	Q235 steel guardrail	2.3	4.6	8.4
Vehicle exit angle / °	GFRP guardrail	2.5	5.6	10.7

As shown in Table 4, all evaluation indicators increase with the impact angle. Under all impact conditions, the GFRP guardrail prevents vehicle penetration, override, and straddling, indicating effective containment capacity.

Under the standard 20° impact condition, the maximum lateral dynamic deflection of the GFRP guardrail is 660 mm, about 6.5% higher than that of the Q235 steel guardrail. This is mainly attributed to the lower stiffness of GFRP. However, the deformation remains acceptable because the vehicle is still effectively contained and redirected.

The GFRP guardrail also shows better cushioning performance. Under the 20° impact condition, the peak resultant acceleration decreases from 178.5 m s^{-2} for the Q235 steel guardrail to 142.3 m s^{-2} for the GFRP guardrail, corresponding to a reduction of 20.3%. The vehicle exit angle of the GFRP guardrail is 10.7°, which is lower than the 12° limit for Class A guardrails. The acceleration histories are compared in Fig. 4.

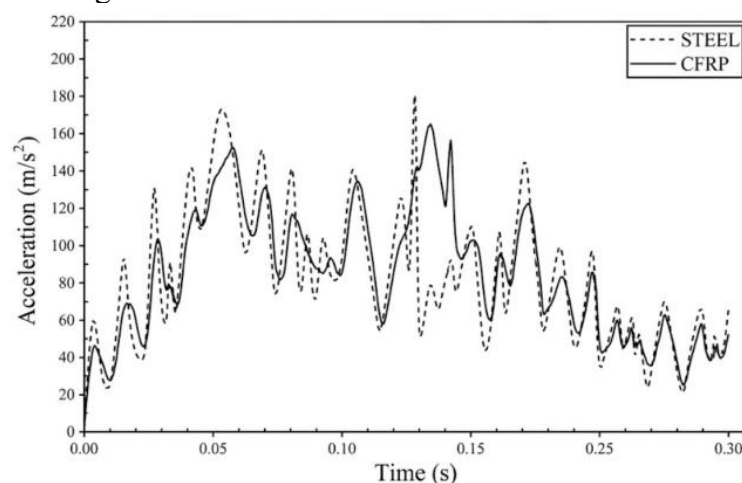


Fig. 4 Comparison of Resultant Acceleration

As shown in Fig. 4, the Q235 steel guardrail produces a higher acceleration peak because of its greater initial contact stiffness. In contrast, the GFRP guardrail reduces the impact peak through structural deformation and progressive composite damage. Overall, the GFRP W-beam guardrail

satisfies the containment and redirection requirements while providing improved cushioning performance.

4.2 Analysis of Life-Cycle Carbon Emissions and Stage Contributions

On the basis that the collision safety performance satisfies the evaluation requirements for Class A guardrails, this study further compares the life-cycle carbon emissions of the GFRP W-beam guardrail and the Q235 steel guardrail. According to the functional unit, system boundary, and carbon emission calculation method established above, the carbon emissions of the two types of guardrails are calculated for five stages: raw material production, component manufacturing, transportation and construction, service and maintenance, and end-of-life disposal. As shown in Table 5, the life-cycle carbon emission results of the GFRP guardrail and the Q235 steel guardrail show significant differences under the same functional unit^[13].

Table 5. Life-Cycle Carbon Emission Results

Life-cycle stage	GFRP guardrail / kg CO ₂ -eq km ⁻¹	Percentage / %	Q235 steel guardrail / kg CO ₂ -eq km ⁻¹	Percentage / %
Raw material production	47,520	72.0	55,180	54.8
Component manufacturing	11,500	17.4	14,280	14.2
Transportation and construction	2,400	3.6	3844	3.8
Service and maintenance	4,000	6.1	31,500	31.3
End-of-life disposal	580	0.9	-4,080	-4.1
Total	66,000	100.0	100,724	100

As shown in Table 5, the total life-cycle carbon emissions of the GFRP guardrail are 66,000 kg CO₂-eq·km⁻¹, while those of the Q235 steel guardrail are 100,724 kg CO₂-eq·km⁻¹. Therefore, the GFRP guardrail reduces emissions by 34,724 kg CO₂-eq·km⁻¹, corresponding to a reduction rate of 34.5%.

For the GFRP guardrail, emissions are mainly concentrated in raw material production, accounting for 72.0% of the total. For the Q235 steel guardrail, raw material production and service-stage maintenance are the two dominant contributors, accounting for 54.8% and 31.3%, respectively. Although steel recycling provides an end-of-life carbon credit, it cannot offset the higher emissions from production and maintenance.

4.3 Sensitivity Analysis

To examine the stability of the life-cycle carbon emission assessment results, this study selected the carbon emission factor of GFRP materials, transportation distance, service-stage maintenance replacement rate, and material recycling rate for $\pm 20\%$ perturbation analysis^[14]. The total life-cycle carbon emissions and emission reduction rates of the two types of guardrails were then recalculated. As shown in Table 6, different parameter perturbations have varying degrees of influence on the emission reduction rate.

Table 6. Life-Cycle Carbon Emission Results under Key Parameter Perturbations

Scenario	GFRP guardrail / kg CO ₂ -eq·km ⁻¹	Q235 steel guardrail / kg CO ₂ -eq·km ⁻¹	Reduction rate / %
Baseline scenario	66,000	100,724	34.5
GFRP material carbon emission factor +20%	75,504	100,724	25.0
GFRP material carbon emission factor -20%	56,496	100,724	43.9

Transportation distance +20%	66,198	101,144	34.6
Transportation distance -20%	65,802	100,304	34.4
Service-stage maintenance replacement ratio +20%	66,800	107,024	37.6
Service-stage maintenance replacement ratio -20%	65,200	94,424	30.9
Material recycling rate +20%	65,989	100,004	34.0
Material recycling rate -20%	66,015	101,540	35.0

As shown in Table 6, the emission reduction rate of the GFRP guardrail remains between 25.0% and 43.9% under $\pm 20\%$ parameter perturbations, indicating that the baseline conclusion is relatively stable. The GFRP material emission factor has the strongest influence, followed by the service-stage cumulative maintenance replacement ratio.

5. Conclusions

(1) The GFRP W-beam guardrail can effectively contain and redirect the vehicle under impact angles of 5° , 10° , and 20° , without penetration, override, or straddling. Under the standard 20° impact condition, the maximum lateral dynamic deflection is 660 mm and the vehicle exit angle is 10.7° , meeting the Class A evaluation requirements.

(2) Compared with the Q235 steel guardrail, the GFRP guardrail shows better cushioning performance. Under the 20° impact condition, the peak resultant acceleration decreases from $178.5 \text{ m}\cdot\text{s}^{-2}$ to $142.3 \text{ m}\cdot\text{s}^{-2}$, corresponding to a reduction of 20.3%.

(3) Under the functional unit of 1 km guardrail over a 50-year assessment period, the life-cycle carbon emissions of the GFRP guardrail are $66,000 \text{ kg CO}_2\text{-eq}\cdot\text{km}^{-1}$, which is 34.5% lower than those of the Q235 steel guardrail. The emission reduction is mainly associated with lower material consumption, lighter transportation demand, and reduced service-stage maintenance replacement.

(4) Sensitivity analysis shows that the GFRP material emission factor and service-stage cumulative maintenance replacement ratio are the dominant parameters affecting the assessment results. Within $\pm 20\%$ perturbations, the emission reduction rate remains between 25.0% and 43.9%, indicating that the low-carbon advantage of the GFRP guardrail is relatively stable.

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