Optimization of a silent mortar baseplate with increased ground contact area

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ABSTRACT

This study presents a parametric optimization of the outer aluminum baseplate of a silent mortar system to improve ground-contact performance while satisfying mass and structural safety constraints. To preserve the system architecture, only the outer baseplate was redesigned, whereas the inner steel baseplate remained unchanged. FEM-based optimization was performed in ANSYS Mechanical under equivalent static recoil loading to evaluate the effects of key geometric parameters on the Von Mises stress, deformation, and minimum safety factor. The optimized design achieved a mass of 5.9 kg, increased the ground-contact area by 53%, and improved the minimum safety factor by 9.8% compared with the original design. Field firing tests under identical soil conditions further reduced settlement by 44.4% after the first firing round and 40.5% after five consecutive rounds. The proposed design effectively improves ground-support capability without compromising structural integrity or operational mobility.

Keywords: Silent mortar; Mortar baseplate; Geometric parametric optimization; Finite element method; Recoil loading; Structural safety factor.

1. INTRODUCTION

Silent mortar systems are widely employed in modern tactical operations because of their compact configuration, high mobility, and low acoustic signature. However, their lightweight baseplates often generate high ground contact pressure, resulting in excessive settlement and reduced firing stability on soft or uneven terrain. Field tests of an existing silent mortar system [1] showed that repeated firing caused significant baseplate settlement, reducing firing repeatability despite the structure remaining within safe stress limits. A previously developed auxiliary baseplate increased the contact area by approximately 50.0%, but the associated increase in system mass reduced operational mobility.

In recent years, the Finite Element Method (FEM) has been widely applied to mortar baseplate design, including parametric optimization, topology optimization, transient recoil analysis, and soil–structure interaction studies [2-6]. Although these studies have improved structural performance, they mainly focus on mass reduction, stress minimization, or dynamic response. The combined optimization of ground-contact area, lightweight design, and structural safety for silent mortar baseplates has received limited attention.

This study presents a parametric geometric optimization of an existing 5.08 kg silent mortar baseplate to increase the ground-contact area by approximately 50.0% while limiting the total mass to 6.09 kg and maintaining at least the original structural safety factor. Structural performance was evaluated using ANSYS Mechanical under equivalent static recoil loading, providing an efficient comparative assessment of the original and redesigned configurations. The proposed approach achieves a balanced improvement in ground-support capability, structural integrity, and lightweight operational mobility.

2. THEORETICAL BACKGROUND AND FINITE ELEMENT MODELING

2.1. Governing equations and structural evaluation criteria

The structural response of the silent mortar baseplate under recoil loading was evaluated using the Finite Element Method (FEM) implemented in ANSYS Mechanical. The baseplate materials were modeled as homogeneous and isotropic using an elastic–plastic constitutive model with bilinear isotropic hardening. Under the applied recoil load, however, the predicted stresses remained below the material yield strength, and no plastic deformation was observed. Under the investigated recoil loading conditions, the maximum equivalent stress remained below the material yield strength; therefore, the structural response was entirely within the elastic regime. The finite element formulation is governed by the constitutive relation and the global equilibrium equation [7-9]:

$$\{\sigma\} = [D] * \{\varepsilon\} \tag{1}$$

$$\{F\} = [K] * \{u\} \tag{2}$$

where {σ} is the stress vector, {ε} is the strain vector, [D] is the elastic constitutive matrix determined from Young's modulus E and Poisson's ratio ν, [K] is the global stiffness matrix and {F} is the external load vector corresponding to the equivalent recoil loading condition.

The structural safety of the baseplate was evaluated using the Von Mises yield criterion for ductile metallic materials subjected to multiaxial loading conditions. The equivalent stress is calculated according to:

$$\sigma_V = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}} \tag{3}$$

where σ_1, σ_2 and σ_3 are the principal stresses.

The corresponding safety factor against yielding is determined by:

$$n_y = \frac{\sigma_y}{\sigma_v} \tag{4}$$

where σ_y is the tensile yield strength of the material. The minimum safety factor was adopted as the primary criterion for evaluating the structural integrity of the baseplate throughout the optimization process.

2.2. Finite element model and numerical configuration

To ensure a consistent comparison, both the original and redesigned baseplates were analyzed under identical finite element conditions in ANSYS Mechanical. A three-dimensional quarter-symmetry finite element model (Figure 1) was established in ANSYS Mechanical to evaluate the structural response under recoil loading.

Figure 1. *Quarter-symmetry finite element mesh model of the original baseplate.*

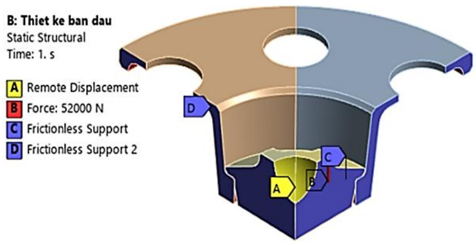

Figure 2. *Recoil loading configuration and boundary conditions used in the FEM analysis.*

Material properties (Table 1), meshing strategy, loading conditions, boundary constraints, and solver settings were applied to both models (Figure 2). Steel was used for the inner baseplate to withstand recoil loads, whereas aluminum alloy was adopted for the outer baseplate to reduce weight while maintaining structural stiffness.

A mesh sensitivity study was conducted using three mesh configurations under identical loading conditions. The minimum safety factor was used as the convergence criterion, with a maximum variation of 1.34%, confirming mesh-independent results. The selected mesh was therefore adopted for all subsequent analyses and optimization.

Table 1. *Mechanical properties of the aluminum alloy used for the outer baseplate.*

No.	Property	Aluminum alloy	Steel	Unit
1	Density	2800	7800	kg/m³
2	Young's Modulus	7E10	2E11	Pa
3	Poisson's Ratio	0.32	0.3	—
4	Tensile Yield Strength	5.03E8	3.72E8	Pa
5	Ultimate Tensile Strength	5.72 E8	6.27 E8	Pa
6	Tangent Modulus	1.0E9	1.5E9	Pa

Table 2. *Mesh sensitivity study based on minimum safety factor.*

No.	Mesh configuration	Number of elements	Minimum safety factor
1	Mesh 1	200000	2.32
2	Mesh 2	242000	2.28
3	Mesh 3	278000	2.25

The numerical analyses were conducted under equivalent static recoil loading corresponding to the estimated peak recoil force under the most severe allowable firing condition. The applied load therefore represents a conservative loading scenario for evaluating the structural integrity of the baseplate assembly. Considering the quarter-symmetry modeling approach, an equivalent load of 52 kN was applied to the analyzed FEM domain, corresponding to a total recoil force of 208 kN acting on the complete baseplate assembly. The applied load was distributed over the recoil load-transfer region of the inner steel baseplate. The applied recoil load of 208 kN represents the maximum design recoil force for a single firing event, including the required safety factor, and was adopted as a conservative loading condition for the structural analysis.

Identical support constraints, including remote displacement and frictionless support conditions, were applied throughout the numerical simulations to ensure consistent structural load-transfer behavior.

Although the simplified loading and support conditions neglect soil dissipation and may slightly overestimate stresses and deformations compared to actual firing tests, they were intentionally applied to both configurations. This approach ensures a consistent and fair comparative evaluation of the structural performance between the original and redesigned baseplates.

3. STRUCTURAL ASSESSMENT OF THE ORIGINAL BASEPLATE

3.1. Geometrical characteristics of the original baseplate

The original silent mortar baseplate assembly consisted of two main components: an inner steel baseplate and an outer aluminum baseplate. Since this study focuses on the redesign and optimization of the outer baseplate, only its geometry is presented in Figure 3, while the inner steel baseplate was retained unchanged. The inner steel baseplate transfers recoil loads from the mortar assembly, whereas the outer aluminum baseplate distributes these loads to the supporting ground.

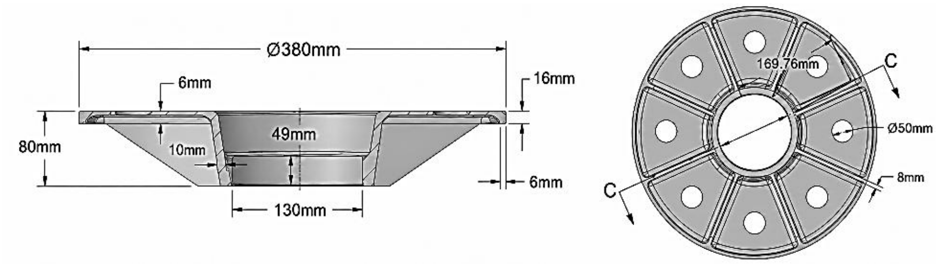

Figure 3. *Geometrical configuration of the original outer aluminum baseplate.*

During firing, recoil loads are transmitted from the inner steel baseplate to the outer aluminum baseplate before reaching the ground-contact region. The outer baseplate adopts a circular geometry with multiple weight-reduction cutouts, local reinforcements, and transition regions to improve load transfer while maintaining sufficient stiffness and low structural mass. The complete baseplate assembly has a total mass of 5.08 kg and serves as the reference configuration for the subsequent structural assessment and optimization.

3.2. Structural performance assessment and optimization strategy

The FEM results showed that the original baseplate experienced a maximum equivalent Von Mises stress of 223 MPa, concentrated around the central socket transition region, and a maximum deformation of 1.1 mm, mainly distributed in the outer support region (Figure 4). Since the maximum stress remained below the aluminum alloy yield strength, the baseplate operated safely within the elastic range under the prescribed recoil loading. The minimum safety factor was 2.25, located near the recoil load-transfer region, confirming that the original design satisfied the required structural safety criteria.

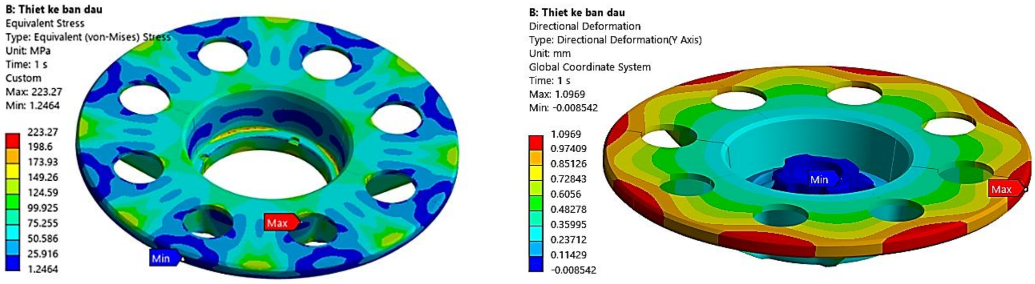

Figure 4. *Equivalent stress and deformation distributions of the original baseplate under recoil loading conditions.*

The safety factor distribution (Figure 5) further showed that Regions 1, 2, and 3 of the outer support exhibited safety factors exceeding 5, while most surrounding areas remained above 4, indicating excess structural capacity and inefficient material utilization.

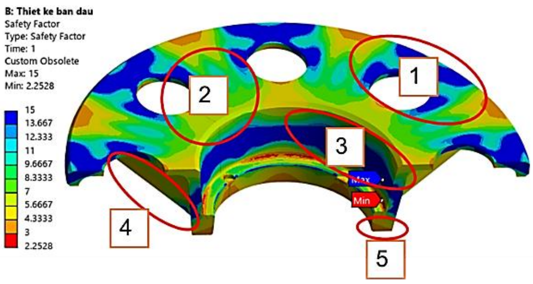

Figure 5. *Safety factor distribution of the original baseplate.*

Based on these results, the optimization strategy focused on redistributing material from the overdesigned regions to enlarge the outer support diameter and increase the effective ground-contact area while maintaining structural safety. The objective was to increase the contact area by approximately 50.0%, limit the total mass to 6.09 kg and maintain a minimum safety factor no lower than that of the original baseplate under identical recoil loading.

4. STRUCTURAL REDESIGN AND PARAMETRIC OPTIMIZATION

4.1. Engineering-driven structural redesign

Based on the structural assessment of the original baseplate, a preliminary redesign was developed using the safety-factor distribution as the design reference. The redesign focused on the outer aluminum baseplate, while the inner steel baseplate and recoil load-transfer structure were retained. The objective was to increase the ground-contact area while limiting mass growth through local thickness modification.

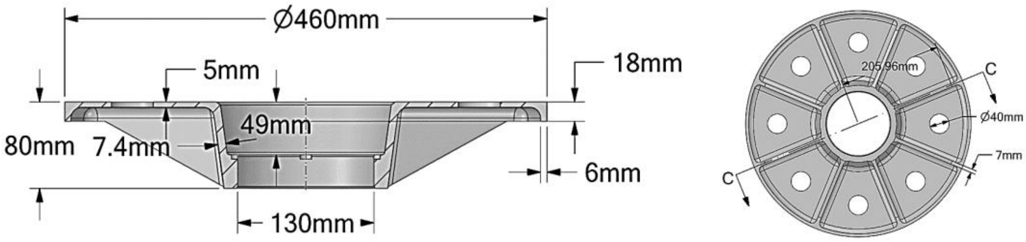

Figure 6. *Preliminary redesigned geometry and principal dimensions of the outer baseplate configuration.*

As shown in Figure 6, the redesigned baseplate adopted an outer diameter of 460 mm to enlarge the ground-contact area. Regions with high safety factors in the original design were locally thinned to improve material utilization, whereas the transition regions were reinforced with thicknesses ranging from 6 to 7.4 mm to maintain stiffness and load-transfer capability. Radial ribs and circular cut-outs were also incorporated to improve load redistribution and reduce unnecessary mass.

The redesigned baseplate achieved a total mass of 5.98 kg, while increasing the effective ground-contact area by approximately 62.0% compared with the original configuration. This design satisfied the preliminary mass and contact-area requirements and was selected for subsequent structural evaluation

4.2. Structural evaluation and optimization framework of the preliminary redesign

The redesigned baseplate was evaluated using the same mesh, loading, boundary conditions, and solver settings described in Section 2.2

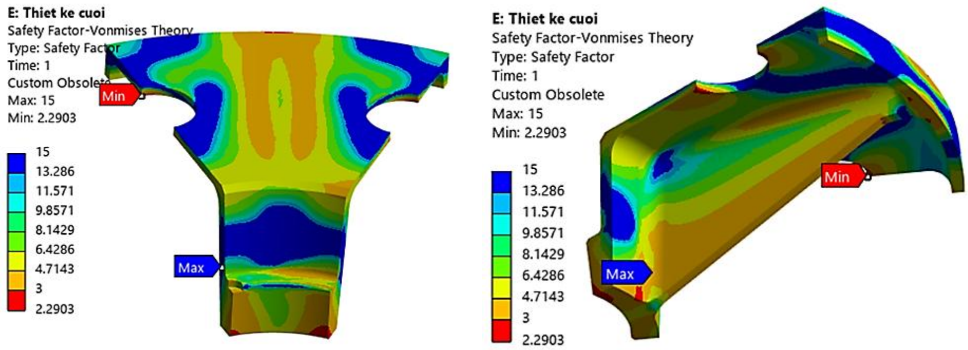

Figure 7. *Safety factor distribution of the redesigned baseplate under recoil loading conditions.*

The FEM analysis yielded a minimum safety factor of 2.29, confirming that the redesigned configuration maintained adequate structural integrity under the maximum recoil load. Considering the 62% increase in ground-contact area and a total mass of 5.98 kg, the redesign satisfied the primary structural and operational requirements. Therefore, it was adopted as the baseline for the subsequent optimization.

To further improve structural efficiency, parametric optimization was performed using ANSYS DesignXplorer. Six geometric parameters were selected as design variables, and a Design of Experiments (DOE) consisting of 45 design points was generated using the Optimal Space-Filling sampling method to ensure a uniform exploration of the design space. The structural responses obtained from the finite element analyses were used to construct a response surface, and the optimal configurations were identified using the Response Surface Optimization method implemented in ANSYS DesignXplorer. The design-variable bounds are listed in Table 3. The lower limits were determined from the validated redesign to preserve structural safety, whereas the upper limits generally did not exceed the original dimensions. The only exception was the outer support radius, whose upper limit was extended to increase the effective ground-contact area.

Table 3. Design variables and parameter bounds for structural optimization.

No.	Design variable	Unit	Baseline value	Lower bound	Upper bound
1	Outer support radius	mm	230	224	230
2	Inner plate thickness	mm	7.5	6.5	8.5
3	Upper plate thickness	mm	5	4.5	6
4	Radial rib thickness	mm	7	6	8
5	Circular-hole distance from center	mm	166	150	180
6	Overall baseplate height	mm	80	78	82

The optimization stage aims to further enhance structural performance while preserving the engineering characteristics achieved during the redesign phase. The optimization objectives and constraints are defined as follows:

Objective function: Minimize the total structural mass of the baseplate.

Structural constraint: Maintain a minimum safety factor greater than 2.4 throughout the structure.

Operational constraint: Preserve an effective ground-contact area increase greater than 50% relative to the original configuration.

Thus, the engineering redesign served as the baseline, and the optimization process refined the geometry to improve mass efficiency without altering the overall design concept.

The optimization generated three candidate designs satisfying all design requirements (Table 4). The candidates exhibited similar geometric parameters and structural performance, indicating convergence toward an optimal design region. The final configuration was selected considering structural performance, mass, and manufacturability.

Table 4. Candidate solutions obtained from the optimization process.

No.	Design variable	Candidate 1	Candidate 2	Candidate 3	Selected design
1	Outer support radius (mm)	224.25	224.05	224.05	224.00
2	Inner plate thickness (mm)	8.23	8.04	8.25	8.00
3	Upper plate thickness (mm)	4.82	4.81	4.83	5.00
4	Radial rib thickness (mm)	6.01	6.01	6.03	6.40
5	Circular-hole distance from center (mm)	170.71	170.68	170.55	170.00
6	Overall baseplate height (mm)	80.40	81.20	80.10	80.00
7	Safety factor minimum	2.47	2.46	2.46	-

The selected design had a total mass of 5.9 kg, representing an increase of only 0.82 kg over the original baseplate while providing an effective ground-contact area of 142,696 mm², approximately 53% larger than the original design.

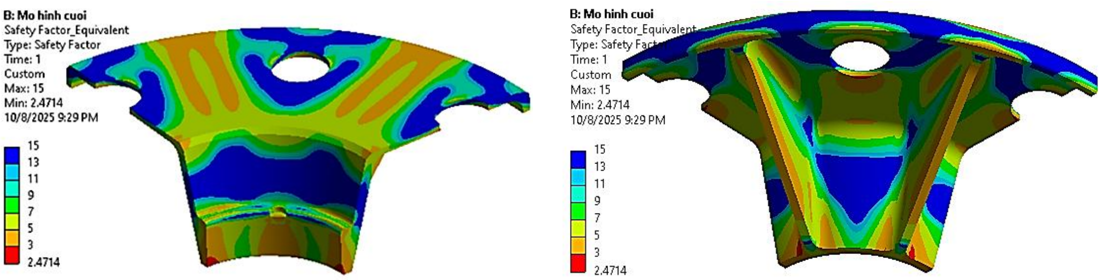

Figure 8. *Safety factor distribution of the final optimized baseplate under recoil loading conditions.*

The optimized baseplate achieved a minimum safety factor of 2.47, located mainly around the central load-transfer and transition regions, while most of the structure exhibited safety factors greater than 3.0. These results confirm that the optimized configuration satisfies the prescribed structural safety requirements under the recoil loading conditions. The corresponding FEM results are presented in Figure 8.

5. EXPERIMENTAL VALIDATION AND DISCUSSION

To validate the optimized baseplate under practical operating conditions, firing tests were conducted using the assembled silent mortar system. The objectives were to verify the structural integrity of the optimized baseplate under repeated recoil loading and to compare its settlement performance with that of the original design.

The tests were performed on relatively uniform natural soft soil under identical firing conditions for both baseplates. The firing location, soil condition, baseplate position, and firing angle were kept as consistent as possible to ensure a fair comparison.

Figure 9. *Experimental setup.*

5.1. Structural integrity verification

Post-test inspections revealed no visible cracks, local damage, or permanent deformation in either baseplate, indicating that both configurations remained structurally safe under repeated recoil loading. These observations agree well with the FEM predictions, which showed safety factors exceeding the design requirement.

The results demonstrate that the optimized baseplate increased the ground-contact area without compromising structural integrity, confirming the effectiveness of the proposed redesign and optimization.

5.2. Settlement performance evaluation

The settlement measurements obtained during the firing tests are summarized in Table 5. For both configurations, settlement increased with the number of firing cycles because of cumulative soil penetration under repeated recoil loading.

Table 5. *Settlement measurements during firing tests.*

No.	Original baseplate settlement (mm)	Optimized baseplate settlement (mm)	Settlement reduction (%)
1	18	10	44.4%
2	28	16	42.9%
3	35	20	42.9%
4	39	23	41.0%
5	42	25	40.5%

The optimized baseplate consistently exhibited lower settlement than the original design throughout all firing cycles. Settlement decreased from 18 mm to 10 mm after the first firing cycle and from 42 mm to 25 mm after five firing cycles, corresponding to reductions of 44.4% and 40.5%, respectively. The improved performance is mainly attributed to the 53.0% increase in effective ground-contact area, which reduced the average ground pressure despite a 16.1% increase in structural mass.

As summarized in Table 6, the optimized baseplate provides simultaneous improvements in structural and operational performance. Compared with the original design, it achieves a 53.0% increase in effective ground-contact area, a 9.8% higher minimum safety factor, and a 40.5% reduction in settlement after five firing cycles, while requiring only a modest 16.1% increase in structural mass. These results validate the effectiveness of the proposed redesign in enhancing ground-support capability while maintaining adequate structural safety.

Table 6. *Comparison between original and optimized baseplates.*

No.	Parameter	Original	Optimized	Change
1	Structural mass (kg)	5.08	5.90	+16.1%
2	Effective ground-contact area (mm²)	93,265	142,696	+53.0%
3	Minimum safety factor	2.25	2.47	+9.8%
4	Settlement after 5 firing cycles (mm)	42	25	−40.5%

6. CONCLUSIONS

This study presented a redesign and FEM-based optimization methodology for improving the ground-support performance of a silent mortar baseplate while maintaining structural safety. A preliminary redesign was first developed and subsequently refined through parametric optimization.

The final design increased the effective ground-contact area from 93,265 mm² to 142,696 mm² (53.0%) while limiting the structural mass to 5.9 kg. FEM analysis predicted a minimum safety factor of 2.47, satisfying the prescribed structural safety requirement.

Experimental firing tests verified the numerical results. No cracks, permanent deformation, or structural damage were observed, and the optimized baseplate consistently reduced settlement by approximately 40.0–44.0% compared with the original design.

Overall, the combined numerical and experimental results demonstrate that the proposed methodology effectively enhances the ground-support capability and operational stability of the silent mortar system on soft ground with only a modest increase in structural mass.

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TÓM TẮT

Tối ưu thiết kế bệ cối triệt âm nhằm tăng diện tích tiếp xúc với mặt đất

Nghiên cứu này trình bày phương pháp tối ưu hóa tham số đối với đế ngoài bằng hợp kim nhôm của súng cối triệt âm nhằm nâng cao hiệu suất tiếp xúc mặt đất khi bắn, đồng thời đáp ứng các yêu cầu về khối lượng và độ bền kết cấu. Để giữ nguyên kiến trúc của hệ thống vũ khí, chỉ đế ngoài được thiết kế lại, trong khi đế trong bằng thép được giữ nguyên. Quá trình tối ưu hóa dựa trên phương pháp phần tử hữu hạn (FEM) trong ANSYS Mechanical với tải trọng giật tĩnh tương đương nhằm đánh giá ảnh hưởng của các tham số hình học đến ứng suất Von Mises, biến dạng và hệ số an toàn nhỏ nhất. Thiết kế tối ưu đạt khối lượng 5.9 kg, tăng 53.0% diện tích tiếp xúc với mặt đất và cải thiện 9.8% hệ số an toàn nhỏ nhất so với thiết kế ban đầu. Các thử nghiệm bắn thực nghiệm trên cùng điều kiện nền đất cho thấy độ lún giảm 44.4% sau phát bắn đầu tiên và 40.5% sau năm phát bắn liên tiếp. Kết quả chứng minh rằng thiết kế được đề xuất giúp nâng cao khả năng đỡ nền mà không làm ảnh hưởng đến độ bền kết cấu hoặc tính cơ động của hệ thống.

Từ khóa: Cối triệt âm; Bệ cối triệt âm; Tối ưu tham số hình học; Phương pháp phần tử hữu hạn; Lực giật khi bắn; Hệ số an toàn kết cấu.