EXPERIMENTAL STUDY ON THE FLEXURAL BEHAVIOR OF TRC-STRENGTHENED REINFORCED CONCRETE BEAMS

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Abstract

This article presents the experimental results on the flexural behavior of reinforced concrete (RC) beams strengthened with textile-reinforced concrete (TRC). Four RC beams were made of B22.5 grade concrete, and the TRC strengthening layer utilized Sigratex Grid 350 textile, with fine-grained concrete Sikagrout 214-11 serving as the binder. The reinforcement layer was applied using a grooving technique. The four-point bending test was conducted to evaluate the improvements in load-bearing capacity and deformation of the beams after strengthening. The results indicated that the strengthened beams exhibited a 36.2% higher load-bearing capacity and a 13.5% increase in mid-span deflection compared to un-strengthened beams. However, the occurrence of debonding in the reinforcing layer reduced the strengthening effectiveness. To ensure the efficiency of flexural strengthening with TRC, attention should be given to the adhesion of the fine-grained concrete layer and additional reinforcement of the compression zone. These findings provide a basis for the practical application of TRC in enhancing RC structures, ensuring both safety and performance.

Keywords: *Textile reinforced concrete; strengthened reinforced concrete beam; four-point bending test; grooving technique.*

1. Introduction

Textile Reinforced Concrete (TRC) primarily consists of fine-grained concrete and high-strength textile reinforcement, such as carbon or glass fiber. TRC exhibits superior mechanical properties, high durability, and better corrosion resistance compared to conventional concrete. TRC is used as a structural material and as a reinforcement to enhance load-bearing capacity and extend the service life of structures [1, 2]. It is an effective solution for improving the load-carrying capacity of reinforced concrete (RC) beams, significantly increasing strength, initial cracking load, and ultimate load capacity, enhancing ductility, and reducing environmental deterioration [3-5].

Experimental and numerical studies on flexural-strengthened beams have shown that ensuring proper bonding between the TRC layer and the existing concrete is critical for effective reinforcement. The adhesion between the fine-grained concrete layer and the old

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concrete surface plays a decisive role in the success of the strengthening solution [6-9]. Therefore, the construction techniques for applying TRC layers to RC beams must be carefully considered. Several methods to enhance the bond between TRC and old concrete include surface roughening and grooving to increase friction between the two layers [5, 10]; the use of bonded anchors and studs to reduce the risk of slippage and delamination between the TRC and concrete [11]; applying U-wraps at the ends, combined with surface bonding, to increase the durability of the TRC-concrete bond [12]; combining external reinforcement with near-surface mounting techniques [13]; and mixing fibers into the matrix to prevent interlayer slippage, a common failure in TRC systems [11].

Among these methods, surface roughening and grooving are cost-effective and easy to implement, making them the most common approach. However, when applied under real-world conditions, this method still requires experimental validation to verify its effectiveness. The objective of this study is to assess the effectiveness of using TRC as a means of enhancing the load-bearing capacity of RC beams when following the grooving-based strengthening method. The research focuses on evaluating the initial cracking load, ultimate load capacity, and mid-span deflection of TRC-strengthened RC beams to determine the method’s efficiency and provide recommendations for practical applications.

2. Flexural test

2.1. Materials for beam fabrication

The RC beams were constructed using conventional B22.5 concrete. For TRC-strengthened RC beams, fine-grained concrete Sikagrout 214-11 was employed, while the strengthening material consisted of textile fibers designated as Sigratex Grid 350. The casting of beams was performed concurrently with the preparation of standard specimens to evaluate the mechanical properties of both types of concrete. The material properties of the carbon fiber textile (Sigratex Grid 350) and steel were provided by the manufacturer. Detailed mechanical properties of the materials are summarized in Table 1 and 2.

Table 1. Material parameters for two types of concrete and fiber

Concrete types	f_c (MPa)	f_t (MPa)	E (MPa)	ν	γ (kg/m^3)
Normal-weight concrete for slabs (B22.5)	39.5	4.1	29540	0.20	2320
Fine aggregate concrete Sikagrout 214-11	74.6	15.2	32600	0.18	2400
Bare fiber bundles Sigratex Grid 350	-	3550	225000	0.22	1740

Table 2. Mechanical properties of steel

E_s (GPa)	ν_s	**Longitudinal Reinforcement AII**		**Stirrups AI**	
		f_y (MPa)	f_u (MPa)	f_y (MPa)	f_u (MPa)
200	0.3	293	385	235	345

2.2. Sample preparation process

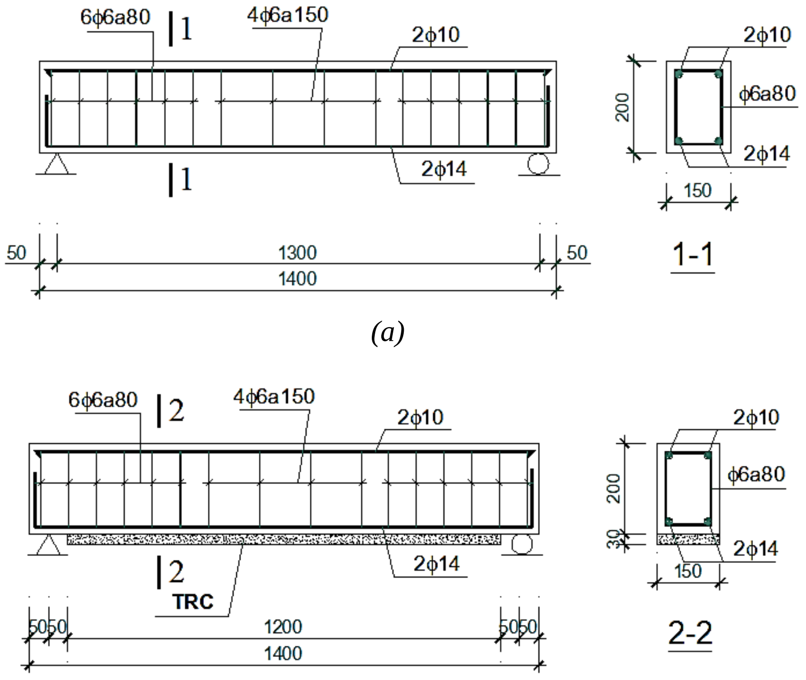
The experimental program involves testing four simply supported reinforced concrete beams. Among these, two beams serve as the reference and are tested until failure for comparison purposes. All beams share identical dimensions and reinforcement details, with a total length of 1400 mm, an effective span of 1300 mm, a width of 150 mm, and a height of 200 mm. For the reinforced concrete beams subjected to bending, failure is primarily caused by moments. Therefore, the stirrups at both ends of the beam are designed with a spacing of approximately 80 mm, while the spacing in the middle region is set at 150 mm to ensure that the beam fails primarily due to bending rather than shear forces. The schematic layout of the beams and the reinforcement details are illustrated in Fig. 1(a). According to the ACI 549.4R-13 technical guidelines, the TRC layer is applied to the underside of the beam, covering the entire beam width (150 mm) and extending along the full length of the beam, excluding the support regions (1000 mm). The thickness of the TRC layers is 30 mm (typically ranges from 20 to 40 mm, depending on the length of the beams). The detail of TRC-strengthened beam can be seen in Fig. 1(b). The properties of the test specimens prepared for the flexural test are summarized in Table 3.

Table 3. Characteristic of beam specimens

Specimen ID	**Specimen dimensions (mm)**	**TRC strengthening dimensions (mm)**	**Number of TRC layers**	**Number of specimens**
DO1-1	1400 × 200 × 150	No		
DO1-2	1400 × 200 × 150	No		
DO2-1	1400 × 200 × 150	Yes, 1200 × 150 × 30	1	1
DO2-2	1400 × 200 × 150	Yes, 1200 × 150 × 30	1	1

Figure 2 and 3 illustrate the process of fabricating unreinforced and reinforced concrete beams. The reinforced concrete beams are strengthened with TRC following these steps:

- The reinforced concrete beams are cured for 28 days before applying the strengthening materials.



(a)

(b)

Fig. 1. Schematic layout of the beam specimens:
a) Unreinforced bending beams; b) TRC-strengthened beam.

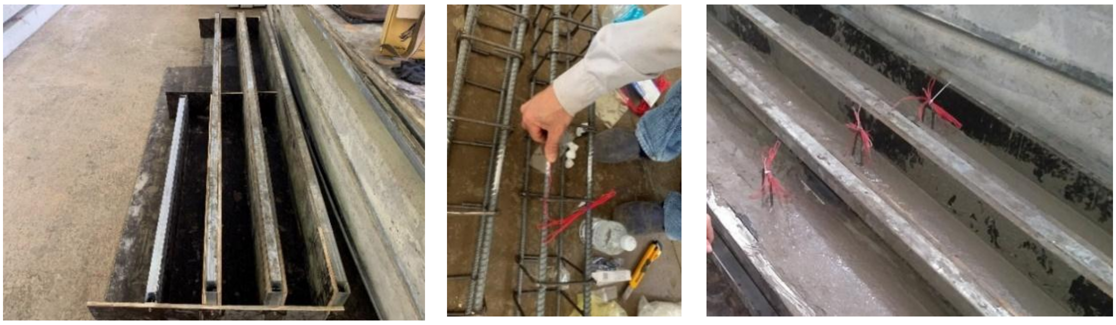


Fig. 2. Fabrication of RC beams (150 × 200 × 1400 mm).

Fig. 3. Casting concrete samples, reinforcing steel, and finishing the surface of the beams.

- A concrete cutting machine is used to create grooves on the surface of the beam at the locations where the strengthening layer will be applied to enhance the bond between the two material layers. First, the surface was moistened with water spraying. Then, the surface grooving technique employs grinding and grooving tools to create grooves with a depth of 2-3 mm and a spacing of 5 cm, as described in reference [5]. Accordingly, the grooves are placed in two perpendicular directions, angled at 45 degrees to the main axis of the beam's bottom surface (Fig. 4).

- The surface is cleaned with compressed air and dampened with water before applying the strengthening layer.

- A layer of TRC strengthening material is adhered to the entire underside of the beam, with a total thickness of 30 mm. The textile mesh is positioned centrally within the strengthening layer.

Fig. 4. Cleaning, roughening the surface, and applying the TRC layer.

2.3. Testing procedure and equipment for bending beams

Experiments were conducted on both unreinforced and reinforced concrete beams. To prevent the beams from slipping off the two supports and to ensure that the tensile reinforcement does not pull out of the concrete during testing, both ends of the beam were supported deep into the supports by 50 mm, and the reinforcement was anchored within the concrete. The experimental setup consisted of a simply supported beam (one fixed support and one movable support) subjected to the action of two concentrated forces, denoted as P. The positions of the applied forces and the beam supports are illustrated in Fig. 5, 6.

A hydraulic jack (20-ton capacity) is used in conjunction with a distributed loading beam, where the concentrated load at the jack head is divided into two equal loads, P, applied to the beam (Fig. 7). The value of the concentrated load at the jack head is determined using a load cell connected to a Data Logger TDS 530 (manufactured by Tokyo Sokki, Japan).

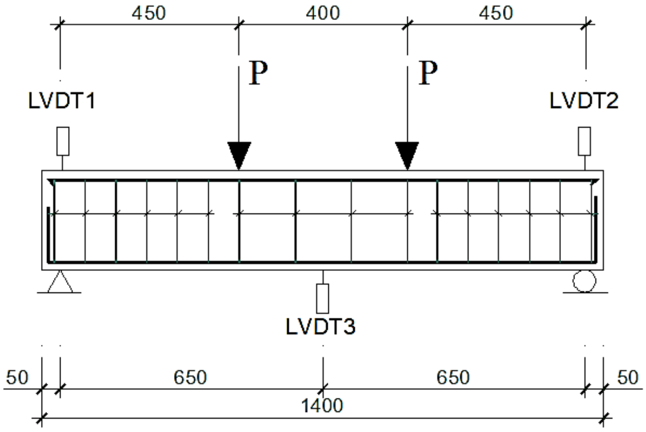


Fig. 5. Experimental setup for unreinforced bending beams.

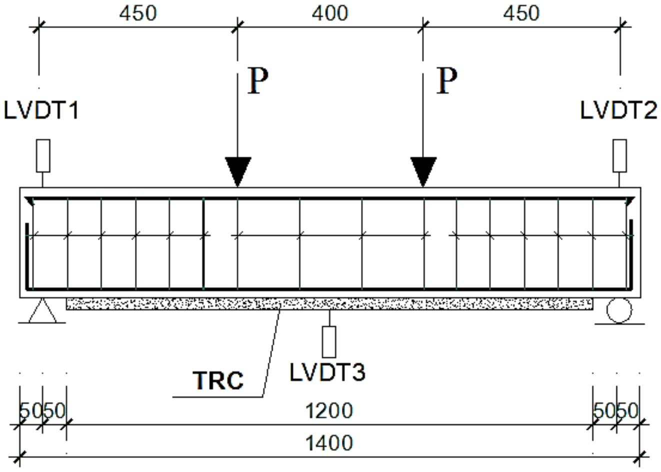


Fig. 6. Experimental setup for TRC reinforced bending beams.

Fig. 7. Loading diagram for TRC reinforced simple beam.

The load parameters applied to the beam, as well as the deflection of the beam at the two supports and mid-span, are transmitted during the experiment. The measuring devices are arranged as follows:

- Load measurement: The load is measured using a load cell.

- Displacement measurement: The displacement of the beam is determined using three Linear Variable Differential Transformers (LVDTs) (with a gain factor K = 100) manufactured by TML, Japan. These devices are positioned at both supports and at the center of the beam.

- The Data logger TDS 530 allows for the automatic and simultaneous recording of measurement parameters (beam displacement and load) during the experiment, and it is connected to a computer (Fig. 8). The data recording mode is set to automatically log data once per second.

Fig. 8. Data logger TDS 530 combined with computer.

2.4. Experiment procedure

After completing the experimental setup, a preliminary loading test was conducted with a load of 2P = 12.0 kN. The purpose of this preliminary load is to eliminate any errors related to the structural assembly and to verify the stability of the system. Once the system and measuring devices were stable, the initial readings were set to zero. The loading on the beam was then applied using a hydraulic jack, with a cylinder displacement rate of 1.2 mm/min. During the loading process, the time of crack appearance was determined based on initial calculations and the strain diagram of the concrete in the tensile region and the reinforcing steel. The load was then increased incrementally.

3. Experimental results

The experimental study evaluated the behavior of both unreinforced and TRC-strengthened reinforced concrete beams subjected to four-point bending. The test results indicated that both configurations led to the failure of the concrete in compression.

Figure 9-11 show that both the strengthened and unstrengthened beams experienced concrete failure in the compression zone. However, for the strengthened beams, the predominant failure mechanism was attributed to the debonding of the strengthening material, despite its high strength. This phenomenon resulted in brittle failure, particularly in some specimens where premature debonding occurred, leading to an ambiguous distinction between the reinforced and unreinforced beams. These results also demonstrate a similarity in the failure mechanisms observed between the experimental outcomes and the numerical simulation results, as reported in [14, 15]. It is important to note that during the experimental assessment of the strengthened beams, instances of premature debonding of the strengthening layer were observed. This resulted in the performance of the strengthened beams being nearly equivalent to that of the unstrengthened beams. This finding underscores the necessity for enhanced attention to and refinement of the bonding techniques employed for the strengthening layer to ensure its effectiveness. Therefore, the failure was not caused by fiber rupture but rather by debonding. Furthermore, in specimens that met the performance criteria, debonding typically occurred in tandem with the failure of the compressive concrete layer. This suggests that the reinforcement of beams subjected to bending should not only concentrate on the underside, where bending moments are pronounced, but also prioritize the enhancement of the compressive concrete layer.

(a) *(b)*

Fig. 9. Unstrengthened beam under bending: (a) before failure and (b) after failure.

(a) *(b)*

Fig. 10. Strengthened beam under bending: (a) before failure and (b) after failure.

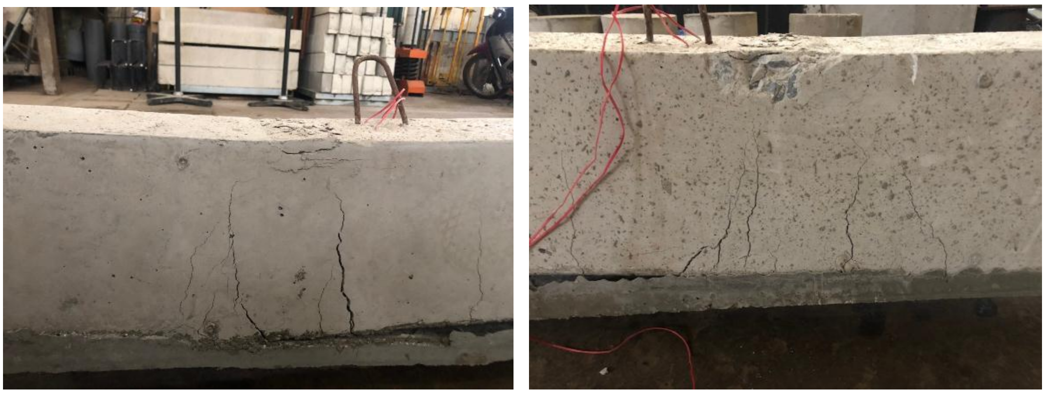


Fig. 11. Flexural cracks in the strengthened beam and failure of the compressive concrete in the strengthened beam.

Figure 12 illustrates the complexity of the structural behavior following reinforcement, attributable to the redistribution of internal forces when the structure is subjected to loading. The incorporation of TRC leads to complete failure of the beam at elevated deformations, particularly when the fiber mesh undergoes tensile rupture. However, if one defines structural failure as occurring upon the debonding of the strengthening layer, this failure manifests abruptly, with the beam exhibiting relatively minor deflections (approximately 12 mm).

Besides, the relationship between total load (2P) and deflection after the elastic phase for the reinforced beams (DT03 and DT04) exhibited a distinct difference, characterized by an initial increase in this load value, followed by a decrease, and then a subsequent increase. The load at which initial cracking occurs in the concrete increases by approximately 18% for the unstrengthened configuration, with the corresponding values being 38 kN and 32 kN, which are approximately 50% of the maximum total load, P_{max}. This behavior is observable in the load-deflection curve, with both the reinforced and unreinforced configurations ending the elastic phase at deflections ranging from approximately 1.8 mm to 2.4 mm. A significant enhancement in stiffness is observed after cracking, whereas no substantial improvement is detected prior to cracking, consistent with findings from previous studies [11].

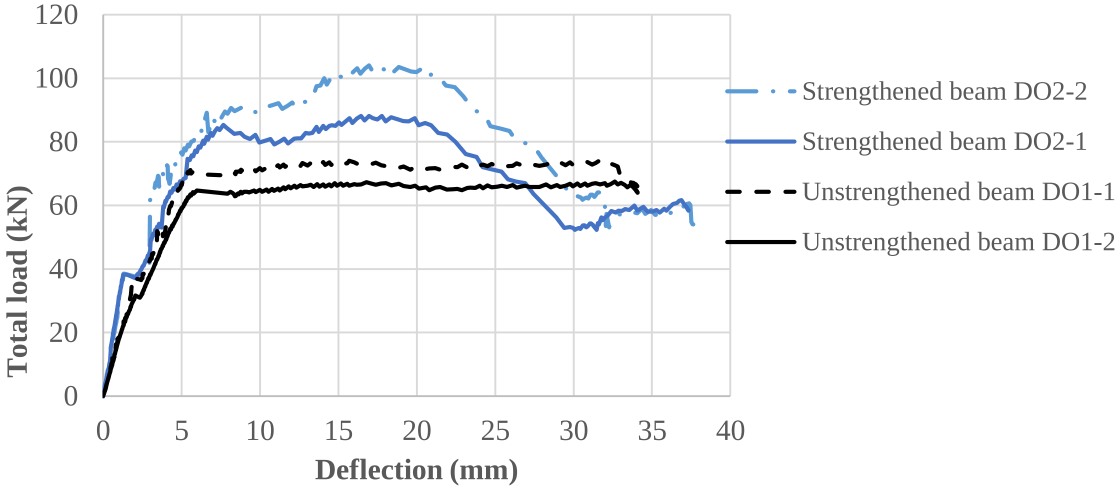


Fig. 12. Load-Deflection curves of experimental beams under bending.

Table 4 and 5 present the results regarding the enhancement of flexural resistance in reinforced concrete beams strengthened with a single layer of carbon fiber mesh. It indicates that when considering failure at the point of compressive concrete failure, the load-bearing capacity of the beams increased significantly by 36.2%, consistent with prior research findings of over 25%. The deflection at mid-span also increased by 13.5% prior to failure. Notably, for the strengthened beams, after the failure of the compressive concrete, the beams did not collapse immediately but continued to exhibit low stress and substantial deformation. This characteristic is significant during usage, providing a warning of potential hazards, thereby ensuring safety for individuals and property. However, when comparing the strengthened configuration to the unstrengthened one, the cracking load in the concrete shows only a slight difference (14.1%), corresponding to a smaller deformation. This indicates an increase in the stiffness of the beam during the elastic phase.

Table 4. Results of failure test

Specimen ID	**Ultimate stage**				**Concrete cracking**			
	Ultimate load P_{max} (kN)	**Average of P_{max} (kN)**	**Deflection Δ_{max} (mm)**	**Average of Δ_{max} (mm)**	**Cracking load P_{crack} (kN)**	**Average of P_{crack} (kN)**	**Deflection Δ_{crack} (mm)**	**Average of Δ_{crack} (mm)**
DO1-1	74	70.5	34.02	33.03	36.57	33.56	1.98	1.97
DO1-2	67		32.04		30.55		1.96	
DO2-1	88	96	37.33	37.48	38.15	38.30	1.53	1.34
DO2-2	104		37.64		38.45		1.15	

Table 5. Evaluation of strengthening effectiveness for flexural beams

Options	**Average unstrengthened**	**Average strengthened**	**Estimate**
P_{max} (kN)	70.5	96	+36.2%
Δ_{max} (mm)	33.03	37.48	+13.5%
P_{crack} (kN)	33.56	38.30	+14.1%

4. Conclusions

Based on the research findings, the following conclusions and recommendations can be drawn:

- When strengthening beams with TRC, special attention should be paid to surface preparation (e.g., cleaning, roughening, etc.) to achieve optimal strengthening performance.

- The application of TRC significantly enhanced the flexural resistance of the beams, ensuring that, after the compression concrete failed, the beams did not collapse immediately. Instead, they continued to sustain low stress and large deformations, providing timely warnings of potential hazards and ensuring safety during service.

- These results suggest that the TRC strengthening method has practical application potential; however, improvements in the construction process are necessary to mitigate early debonding. Additionally, strengthening efforts should not only focus on the beam's underside but also consider the compression concrete region to enhance the load-carrying effectiveness of the structure.

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NGHIÊN CỨU THỰC NGHIỆM ỨNG XỬ UỐN CỦA DẦM BÊ TÔNG CỐT THÉP GIA CƯỜNG BẰNG TRC

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Tóm tắt: Bài báo trình bày kết quả nghiên cứu thí nghiệm để kiểm chứng khả năng chịu uốn của dầm bê tông cốt thép (BTCT) gia cường bằng vật liệu bê tông cốt lưới dệt (TRC). Bê tông chế tạo cho 4 dầm BTCT là loại B22.5, lớp gia cường TRC sử dụng loại lưới Sigratex Grid 350 và bê tông hạt mịn Sikagrout 214-11 làm chất kết dính. Phương pháp thi công lớp gia cường tạo khía rãnh. Thí nghiệm uốn 4 điểm được tiến hành nhằm đánh giá sự cải thiện khả năng chịu lực và biến dạng của dầm sau khi gia cường. Kết quả cho thấy dầm gia cường có khả năng chịu tải cao hơn 36,2% và tăng 13,5% chuyển vị tại giữa nhịp so với dầm không gia cường. Việc xuất hiện hiện tượng bong tách lớp gia cường làm giảm hiệu quả gia cường. Để đảm bảo tính hiệu quả trong gia cường cho dầm chịu uốn bằng TRC, cần quan tâm nghiên cứu đến khả năng bám dính của lớp bê tông hạt mịn và tăng gia cường thêm vùng bê tông chịu nén. Những kết quả này đóng góp cơ sở cho việc ứng dụng vật liệu TRC trong tăng cường kết cấu BTCT, đảm bảo an toàn và hiệu quả trong sử dụng thực tế.

Từ khóa: *Bê tông cốt lưới dệt; dầm bê tông cốt thép gia cường; thí nghiệm uốn bốn điểm; kỹ thuật tạo rãnh.*

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