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†Research Paper

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Structural performance assessment of demountable GFRP dowel bar

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ABSTRACT

For jointed precast concrete pavements, this study suggests a novel demountable dowel bar system made of glass fiber reinforced polymer (GFRP). The conventional steel dowel systems have limited reuse, corrosion, and concentrated stress. On the other hand, the suggested solution features a stainless steel sleeve that accommodates the GFRP bar, providing both removability and durability. Under monotonic loading circumstances, four slab specimens measuring 300 mm, 400 mm, and 800 mm in width were put to the test. The findings demonstrated that, in contrast to specimens with traditional steel dowels, those with GFRP dowels had distinct failure processes. The suggested system's potential application in modular pavement systems was indicated by its encouraging load-bearing capability and flexibility.

1. Introduction

In current days, highly used highway networks have heavy traffic that requires repair and maintenance because pavements composed of less durable materials, such as early-strength concrete and asphalt, are prone to deterioration within five to ten years [1–3]. Road closures must be prolonged in order to repair damaged pavements and guarantee that the concrete reaches a strong enough level. It may be inferred that the economic effects will exceed 160 billion euros. by 2025 as a result of traffic jams [4]. Additionally, the U.S. Federal Transit Administration (FTA). As a result, quick pavement construction and maintenance methods steadily gain importance. For almost 40 years, precast concrete pavement (PCP) has been developed, allowing off-site manufacturing and assembly of prefabricated modules [1, 2]. When the precast concrete pavement is ready and strong enough, it is delivered to the building site and set up on a foundation that has already been built [1, 2, 5, 6]. When compared to an on-site system, several differences and benefits can be identified, which will be listed as follows:

- High curing and quality: The concrete casting process is carried out under controlled temperature and humidity conditions by skilled workers with experience in concrete casting [1, 2, 7–9].
- Minimum road closures: since the concrete is precast and requires little on-site work, the installation can be completed quickly, or possibly during nighttime [7, 10–12].
- Increased constructability. Construction efficiency is increased by the use of cutting-edge tools and methods in precast concrete pavement (PCP) technology [2, 3].

In modern pavement, precast concrete (PCP) is used for construction and maintenance. it is also utilized because of its great durability in a variety of applications [3, 7]. In order to reduce the stress and deflection created in the loaded pavement slab, epoxy-coated steel dowel bars are commonly used as load transfer devices to shift some of the load to the unloaded slab [1, 2, 13–18]. However, there are still serious issues that limit the joint's capacity to tolerate wheel stresses even after it has been in widespread use for more than a century [19].

- Dowel bar steel corrosion: The corrosion of steel bars is caused by the easy deterioration of the epoxy coating under fatigue stress, resulting in steel corrosion and chloride ion exchange [13, 18, 20, 21].
- Decrease in Freedom of Movement: Concrete pavements are subjected to high stress due to the deterioration of dowel bars. Therefore, the dowel bars cannot move freely, causing the pavement surface to develop transverse fissures as the concrete shrinks as a result of weather variations [1, 2, 22].
- High Concentration of Stress: The concrete along the dowel bar has four crucial zones. When subjected to a vertical force, the concrete undergoes local crushing due to the Concentration of compressive stress at the dowel bar's top and bottom [13, 17, 23–25].

Tensile stress concentration on the dowel bar's sides comes next, leading to the formation of microcracks [21, 26–30] . Figure 1 shows the distributions of compressive and tensile stress within the dowel slot under vertical load. Because the tensile stress distribution is symmetric, only half of it is displayed.

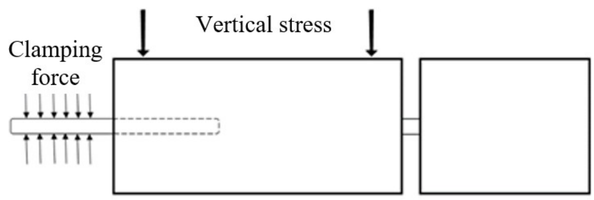

Figure 1. The concrete pavement under vertical load.

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Nomenclature

ASTM	American Society for Testing and Material	*LVDT*	Linear Variable Differential Transformer
D	Diameter	*mm*	Millimeter
GFRP	Glass Fiber Reinforced Polymer	*t*	Thickness
KN	Kilo newton	*UHPC*	Ultra-High Performance Concrete
LTE	Load Transfer Differential	*W*	Width

To avoid most of the issues mentioned above, pavement must be carefully and precisely designed to build durable precast concrete sidewalks [1]. To prevent corrosion, it is recommended to use materials that are resistant to corrosion, like glass fiber-reinforced polymer (GFRP), for manufacturing dowel bars [13, 17, 18, 27, 31–33]. To reduce the concentration of high compressive and tensile stresses, it is recommended to design pavement joints with huge areas where steel and concrete come into contact [17, 34, 35]. Furthermore, Demountability may be necessary, particularly when designing reusable concrete pavement systems. Rapid-setting materials are used to grout the dowel bar holes in traditional JPrCP systems [1, 2]. Due to the rapid setting of these materials, their removal becomes very difficult, especially when they deteriorate during service life. Consequently, it is important to design precast concrete pavement systems with flexible, removable joints for removal and replacement. The paper's goal is to provide a novel demountable dowel bar connection mechanism that alleviates the extreme concentration of tension at the joint surface. The design of the detachable dowel bar connection minimizes the disadvantages of the traditional dowel bar connection while optimizing the advantages of precast concrete pavement technology. The design of the detachable dowel bar connection minimizes the disadvantages of the traditional dowel bar connection while optimizing the advantages of precast concrete pavement technology. Then, using concrete blocks with the detachable dowel bar connection, the ultimate load and distribution are experimentally evaluated under monotonic load. The previous studies Recent studies have investigated the feasibility of using Glass Fiber Reinforced Polymer (GFRP) dowels and demountable slab systems as alternatives to traditional jointed concrete pavement (JPCP) with steel dowels. The authors in [35] conducted a comprehensive evaluation of GFRP dowels under cyclic wheel loading and misalignment conditions. The study showed that GFRP dowels maintained high load transfer efficiency (LTE) even with poor alignment, while also reducing concrete cracking and pull-out stress, indicating greater tolerance to installation imperfections. Similarly, the work in [36] examined the performance of 38 mm GFRP dowels embedded in full-scale JPCP sections. Their results revealed that after one million loading cycles, the GFRP dowels maintained LTE comparable to or better than traditional steel, filling a major research gap in long-term durability assessment. GFRP dowels exhibited LTE ranging from 86% to 100%, confirming their structural suitability even under suboptimal subgrade conditions. Meanwhile, [37] reported that both 25 *mm* and 38 *mm* GFRP dowels exceeded the 81% LTE threshold across multiple test configurations, despite the absence of clear national design guidelines for FRP materials in pavement applications. Ultra-High Performance Concrete (UHPC) link slabs have been employed in recent studies to replace conventional steel dowel bars in jointed rigid pavements, increasing their performance and longevity. The application of a short UHPC link slab as a substitute load transfer mechanism in rigid pavements was experimentally examined by [38]. Their findings showed that, in comparison to traditional dowelled joints, UHPC joints showed substantially less deflection and relative movement. Regardless of joint width, the UHPC system also demonstrated improved fracture management and increased load-carrying capability (up to 23.3% higher). These results demonstrated UHPC's feasibility as a long-lasting, low-maintenance option for high-performance pavement systems. Several recent studies have investigated the application of ultra-high-performance concrete (UHPC) link slabs as a substitute for traditional dowelled joints in rigid pavements. [39] explored the development of jointless rigid pavement systems using UHPC link slabs, highlighting the material's high durability, crack resistance, and ability to eliminate the need for conventional joints. Their findings demonstrated that UHPC could maintain structural continuity and accommodate thermal movements while minimizing long-term maintenance requirements. In a more detailed performance-oriented study, (Aljelawy et al., 2025) examined the advantages of UHPC link slabs in terms of structural efficiency and durability compared to steel dowel bars. Through experimental analysis and case evaluation, the authors concluded that UHPC slabs offer superior resistance to spalling, corrosion, and joint degradation, making them a sustainable and technically sound alternative for modern pavements. Further advancing the field, [40] conducted finite element simulations to assess the behavior of shear stud-reinforced UHPC link slabs connecting plain concrete pavement segments. Their results revealed that the inclusion of shear studs significantly improved load transfer between slabs, reduced stress concentrations, and enhanced the fatigue performance of the joint system. These outcomes underscore the practical potential of integrating UHPC link slabs with mechanical connectors in real-world pavement applications. [41] built on these experimental findings by simulating the structural behavior of jointed concrete slabs coupled with UHPC link slabs by a thorough finite element analysis using ABAQUS. Concrete Damage Plasticity for the concrete and elastic-plastic behavior for implanted steel shear connections were two examples of actual material qualities that were included in their model. With up to 100% agreement in load-displacement response and 92% accuracy in load transfer efficiency (LTE), the numerical findings closely matched the actual data. The ideal link slab dimensions for various joint widths were further determined via parametric research. All of these studies provide credence to the increasing body of evidence showing that UHPC link slabs may improve joint performance, durability, and service life while successfully replacing steel dowel systems. There is a clear research gap concerning removable concrete pavement systems, particularly in evaluating their structural performance and cost-effectiveness. Despite their potential to accelerate maintenance operations and reduce long-term repair costs, such systems remain under-investigated compared to traditional pavement solutions.

2. Demountability mechanism

Given that the primary objective of the purpose of the proposed demountable dowel bar connection is to, each pavement slab must be built and repaired separately. The installation procedure involves placing a GFRP dowel bar inside a single slab of pavement, then, after the second paving slab has been properly positioned, inserting the placed dowel bar into the next slab from the top slot. As soon as the dowel bar shifts to the desired position, a thin plastic sheet will cover the top slot; this sheet When the pavement slab needs to be replaced, it can be taken out. The dowel bar is then forced into the block of pavement next to it. After that, a new pavement slab is installed in lieu of the damaged one. Figures 2 and 3 illustrate the overlapping and removal of the dowel bar with the stainless steel tube.

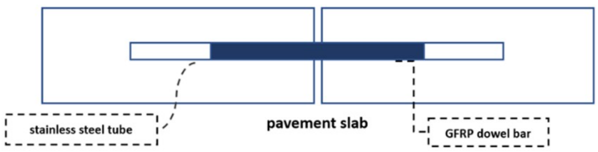
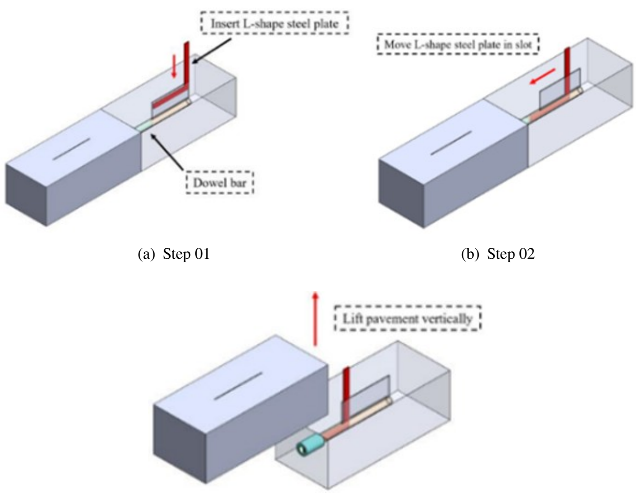


Figure 2. Stainless steel pipe overlap with GFRP dowel bar.



(a) Step 01 (b) Step 02

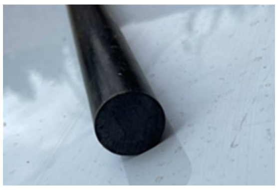
(c) Step 03

Figure 3. Removal mechanism

3. Material and method

3.1 Material

Portland cement, fine and coarse aggregates, GFRP dowel bars (25 *mm* in diameter), and stainless steel tubes (4 *mm* in thickness) are the main components utilized. A steel tube encloses a GFRP bar to facilitate its movement and removal from the dowel bar system. With a water-to-cement ratio of 0.5 and a concrete mix ratio of 1:1.5:2.4, the concrete was intended to have a target compressive strength of 30 *MPa*. All materials are shown in Fig. 4.


(a) Solid bar


(b) Tube bar


(c) Full bars

Figure 4. All materials

3.2 Specimens and test steps

In this research, the structural performance of specimens and a detachable dowel system was evaluated using the modified AASHTO T253 specification in the structural engineering laboratory at Al-Qadisiyah University. The testing program included four main specimens, as shown in Table 1.

Table 1. Show the specimen properties.

Specimen ID	Dowel bar diameter (*mm*)	Tube external diameter (*mm*)
25D300W	25	—
25D4T300W	25	34
25D4T400W	25	34
25D4T800W	25	34

The first specimen was a reference specimen with standard dimensions. The second specimen was constructed with the same dimensions as the reference specimen, with the main variable of using a stainless steel tube and a glass fiber reinforced polymer (GFRP) dowel. The third specimen was designed with a width of 400 *mm* and was also equipped with a stainless steel tube and a GFRP dowel to study the effect of reducing the specimen width. The fourth specimen was designed with a width of 800 *mm*, using the same stainless steel tube and GFRP dowel system, to study the effect of increasing the specimen width on the ultimate load and stress distribution. A uniform height of 200 *mm* was maintained for all specimens to ensure consistent test conditions and achieve accurate and comparable results. Figure 5 shows the casting of the samples. Note: 25D represents the 25 *mm*-diameter of GFRP dowel bar; 4T refers to the 4 *mm* thick tubes made of stainless steel, respectively; the 300, 400 and 800 W mean the width for samples. "These variations in specimen configuration were designed to evaluate their influence on load-carrying capacity and stress behavior, providing a comprehensive understanding of how geometry and confinement affect structural performance under applied loads.

3.3 Test methodology

A controlled laboratory environment was used for the experimental program. High-performance concrete was used to cast each specimen, following ASTM C192 standards for mixing, placing, and curing. The specimens were marked and ready for testing after a 28-day curing period. Standardized mechanical tests were conducted prior to testing to verify the concrete material properties. The workability and compressive strength of the concrete were evaluated using the cube compression test and the slump test shown in Fig. 6, and the average compressive strength was 29.7 MPa at 28 days. For GFRP, the properties were verified based on the manufacturer's tests, which included detailed mechanical properties. Universal testing equipment with a load capacity of 1,000 kN was used to test the specimens (four specimens total) under static stress. Realistic boundary conditions were established by placing each slab on top of a simply supported structure. Using a hydraulic actuator, a constant vertical force was applied three inches from the edge of the slab until failure. An LVDT (Linear Variable Differential Transformer) was installed at the center of the concrete subsurface of the specimens to accurately measure vertical displacement during loading. Before testing, the gauges were calibrated according to the manufacturer's instructions and confirmed through mock tests. To prevent noise or signal drift during data collection, we ensured that the gauges were properly connected and aligned. We maintained the loading rate at 2mm/min, and all experiments adhered to an identical loading methodology to ensure consistency and facilitate accurate comparisons


(a) Model 01


(b) Model 02


(c) Model 03


(d) Model 04

Figure 5. Samples casting.


(a) Cubes

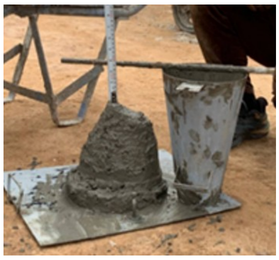

(b) Slump

Figure 6. Cubes and Slump test.

4. Discussion of results

4.1 Cracks and failure mode

The peak load and matching displacement for each examined specimen are shown in Table 2. The findings showed a considerable difference in the structural behavior of the suggested demountable GFRP dowel systems and the traditional steel dowel control specimen, especially with regard to the load-displacement response and failure mechanism. With a displacement of 7.76 mm and the greatest peak load of 89.06 kN, the control specimen (25D) using a steel dowel demonstrated the highest performance. Concrete crushing at the dowel-concrete interface caused the failure to develop in a brittle way, which is common in stiff systems with high stress concentration. Despite having a high load capacity, the failure mode restricts reparability and raises questions about longevity because of possible long-term corrosion. The 25D4T300W, 25D4T400W, and 25D4T800W specimens with GFRP demountable dowel systems, on the other hand, showed a distinct structural reaction, as evidenced by a change in failure mode from concrete crushing to dowel shear. This change demonstrates the GFRP bars' increased ductility and capacity to absorb energy. Depending on the geometric arrangement, the total applied force for these specimens varied from 90.4 kN to 95.0 kN, which is equivalent to or even more than that of the control specimen. With a displacement of 15.07 mm, the

25D4T300W specimen had the highest ductility, demonstrating that GFRP can withstand greater deformations without experiencing catastrophic failure. Despite having a comparable load capacity, the 25D4T800W specimen showed less ductility, maybe as a result of its wider spacing and less transverse confinement. These results demonstrate that the demountable GFRP dowel system may provide notable benefits such as corrosion resistance, long-term durability, and removability while achieving structural performance on par with steel. Additionally, the shift in failure mode from concrete crushing to controlled dowel shear makes service conditions safer and more predictable. Crucially, the GFRP examples showed no discernible concrete spalling or cracking, supporting the notion that failure was restricted to the dowel system itself. In actuality, this behavior is beneficial as it makes pavement slab maintenance, replacement, and inspection simpler. Typical failure patterns for both steel and GFRP systems are shown in Fig. 7.

Table 2. Test results of pavement samples.

Samples	Load, KN on one side	Vertical displacement	Failure mode
25D	89.06	07.76	Compression failure
25D4T300W	46.80	15.07	Dowel bar shear failure
25D4T400W	47.50	10.66	Dowel bar shear failure
25D4T800W	45.20	07.37	Dowel bar shear failure

(a) Model 01 (b) Model 02

(c) Model 03 (d) Model 04

(e) Model 05 (f) Model 06

Figure 7. Cubes and Slump test.

4.2 Load-displacement behavior

To investigate the structural response of precast concrete pavement systems utilizing GFRP dowels, a comparative analysis was conducted against a conventional reference specimen reinforced with steel dowels, Fig. 8, which illustrates the comparative load-displacement responses for all specimens. The load-displacement behavior of specimens with varying slab widths (300 mm, 400 mm, and 800 mm) was assessed to determine the influence of geometry on strength, deformability, and failure mechanisms. The reference specimen, reinforced with a conventional steel dowel, exhibited the highest peak load of 89.06 kN at a displacement of 7.76 mm. In contrast, GFRP-doweled specimens demonstrated distinct load and deformation characteristics that varied with slab width. The 300 mm-wide slab achieved a peak load of 46.8 kN at a displacement of 15.07 mm, indicating greater ductility but significantly reduced strength compared to the steel reference. The 400mm-wide slab recorded the highest total capacity among the GFRP group, 47.5 kN per side (95.0 kN combined)-at a moderate displacement of 10.66 mm. The 800 mm specimen exhibited a slightly lower total load of 90.4 kN (45.2 kN per side) with the smallest displacement among GFRP slabs at 7.37 mm, signaling reduced deformability and possible confinement-related stiffness.

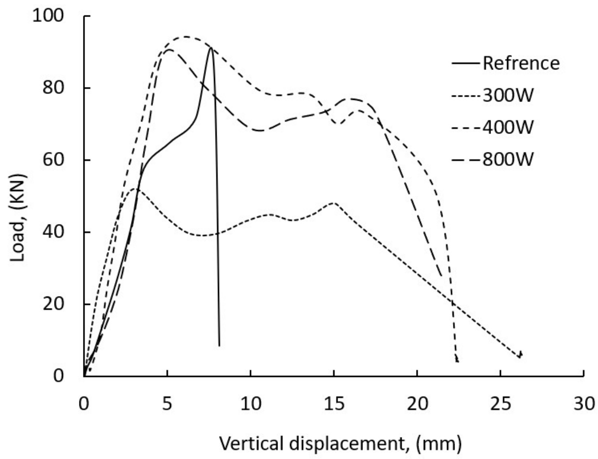


Figure 8. Graph of load displacement for deferent width sample and control slab.

Analyzing the results in relative terms, when load capacity is normalized to the reference specimen on a per-side basis, the 300 mm, 400 mm, and 800 mm GFRP slabs achieved 52.5%, 53.3%, and 50.7% of the steel-doweled specimen's capacity, respectively. However, when both sides of the GFRP-supported slabs are considered, the 400 mm and 800 mm slabs exceeded the total peak load of the reference specimen by 6.7% and 1.5%, respectively. This shift in comparative performance underscores the importance of evaluating symmetrical slab systems holistically rather than on a per-side basis alone. Moreover, the relationship between displacement and peak load reveals a trade-off between strength and ductility. The 300 mm slab, despite its lower strength, exhibited the highest displacement, implying a more gradual failure and higher energy absorption. In contrast, the 800 mm specimen, though comparable in total load to the reference, showed early failure at a lower displacement, raising concerns about its capacity to sustain deformation without brittle failure. Notably, the 400 mm specimen achieved the highest load among all configurations, but its moderate displacement suggests an optimal balance between stiffness and deformability-albeit with reduced post-peak ductility. These results highlight the sensitivity of demountable GFRP dowel systems to geometric parameters, particularly slab width and dowel spacing. The findings indicate that increasing slab width may enhance total load-bearing capacity but can also reduce ductility, potentially affecting long-term performance under dynamic or repeated loads.

5. Conclusion

This work proposes and validates a demountable GFRP dowel bar system for precast concrete pavements. According to testing results, the technology is very appropriate for modular pavement applications as it allows full slab removability and exhibits an effective load transmission capacity. When compared to conventional steel, the use of GFRP dowels may result in certain ductility restrictions; however, these are outweighed over time by the benefits in terms of system resilience, simplicity of maintenance, and longevity. The suggested system's ability to lower life-cycle costs is one of its main benefits. The use of specific GFRP dowels and stainless steel sleeves may result in somewhat higher initial construction costs, but over time, the substantial decrease in maintenance frequency and repair interventions translates into cheaper overall ownership costs. The pavement's useful life is increased by the corrosion-resistant qualities of GFRP materials, which remove the typical deterioration problems with steel dowels, especially in areas that are moisture-sensitive or chloride-rich. Future studies should use full-scale fatigue testing and sophisticated finite element models that take into consideration dowel–slab contact, temperature effects, and moisture-driven deterioration in order to thoroughly assess the long-term performance and improve the design of such systems. All things considered, the suggested demountable GFRP system is a viable path toward robust and sustainable pavement infrastructure with reduced long-term costs and longer service life. Finally, based on the findings of this study, the following recommendations are proposed:

- Further experimental investigations on the long-term performance of demountable GFRP dowel bars under cyclic loading.
- Comparative studies using different GFRP compositions and surface treatments to enhance bond performance.
- Numerical modeling and finite element analysis to predict the behavior of demountable connections under varying loading conditions.
- Investigation of the cost-benefit analysis for adopting demountable dowel systems in large-scale pavement projects.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

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This study didn't receive any specific funds.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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