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Research Article

Development of a Prestressing CFRP Laminate Anchorage System and Bridge Strengthening Application

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For prestressed carbon fiber reinforced polymer (CFRP) tendon anchorage systems to become well established and used on a large scale, practical requirements for structure strengthening may be met by performing a relatively easy anchorage technique using prestressing CFRP laminates. From testing performed on a clip-type CFRP laminate anchorage system developed in our research group, it was revealed that this system could achieve the anchorage efficiency and the relaxation met the requirement of specification. Furthermore, the relevant indices of the anchorage system met the prestressed system standards. A test on the load-carrying capacity of a full-scale model beam demonstrated that the load-carrying capacity of the beam increased by more than 60% after it was strengthened with the anchorage system. The prestressing CFRP laminates and the bridge structure deformed and bore stress as a composite and exhibited excellent operating performance when working together.

1. Introduction

During decades of rapid transportation construction, a large number of bridges were built in China. Now, these bridges have entered into a period in which deterioration and accidents are occurring at high frequencies. The deteriorated condition of these bridges is caused in part by natural weathering and in part by techniques used to construct the bridges. Evidently, engineering quality, traffic volumes, sharp load increases, and later-stage management and maintenance are key factors that lead to frequent accidents.

According to some statistics [1], by the end of 2015, China's highway system had nearly 800,000 bridges with a total length of 45,930,000 m. China was ranked number one in the world in terms of the number of bridges as well as the total length of bridges. Of the 800,000 bridges, approximately 200,000 currently require strengthening. According to statistics from the relevant departments of the China Academy of Railway Sciences, the load levels of 170,000 bridges with a span of less than 32 m in China's railway system need to be increased from 250 kN to 300 kN to meet the development needs of railroad transportation [1, 2]. In the cities, because of the rapid development of transportation structures, a particularly large number of overpasses and interchanges require maintenance and strengthening.

The majority of the bridges in China that are currently in service are constructed with reinforced concrete or prestressed concrete. Because of the increases in traffic volumes and the number of overloaded vehicles, damage has occurred to a relatively large number of bridges; these damaged and unsafe bridges affect safe transportation and development. To repair damaged bridges that are still in service, researchers around the world have studied various strengthening techniques [3–5]. The following are common bridge strengthening techniques:

(1) Increasing the cross section: increasing the area of concrete that is under pressure or increasing the number of load-bearing rebars using the chemical rebar grouting method in the weak section of a component.
(2) Strengthening by bonding: bonding steel plates or fiber-reinforced polymer (FRP) composites (e.g.,

fiberglass, aramid FRP sheets, and carbon fiber) to the area of a component that is under tension using a chemical adhesive to share a portion of the tension that the rebars in this area experience [6].

(3) Strengthening the component by applying an external prestress: externally adding prestressed steel strands to the girder to counter a portion of the bending moment.

(4) Changing the structure system: adding bearings or piers to the bottom of simply supported beams or connecting two simply supported beams to form a continuous beam to increase the load-carrying capacity of the bridge.

(5) Strengthening with prestressed carbon fibers: tensioning components requiring strengthening with prestressed epoxy resin adhesive-coated carbon fibers to repair the deformation-induced and closed cracks in the beams and then bonding and anchoring carbon fiber laminates onto the components to increase their load-carrying capacity [7–9].

Currently, unidirectional carbon fiber sheets are predominately used in structure strengthening, while bidirectional carbon fiber sheets are extremely rarely used. Carbon fiber plate materials, including carbon fiber laminates and carbon fiber strips, are produced by curing and extruding resin and fiber yarns that are mixed at a certain ratio at a high temperature. Compared to products bonded with multiple layers of carbon fiber sheets, products bonded with carbon fiber laminates have better assured quality. They can withstand load more evenly and bring the strength of carbon fiber laminates into full play [10–12]. Carbon fiber materials are significantly advantageous in structure strengthening because of their high strength, low density, and corrosion resistance.

While carbon fiber materials have clear advantages, structure strengthening methods that involve bonding the structure with carbon fibers have certain limitations and difficulties, mainly in two areas [13–15]. (1) Carbon fiber sheets have low-strength utilization efficiency (less than 15%). The elastic modulus of carbon fiber sheets is comparable to that of rebars used in concrete structures, whereas the strength of carbon fiber sheets is more than 10 times greater than that of rebar. As a result, carbon fibers have extremely low-strength utilization efficiency when employed to strengthen concrete structures using the conventional bonding method. (2) Debonding between the carbon fibers and concrete leads to premature failure of the strengthened structure. Debonding failure of a structure strengthened by bonding with carbon fiber sheets using the conventional bonding method occurs because of excessive bond stress in localized areas and a normal force resulting from an uneven structure surface.

Therefore, it is necessary to develop new strengthening techniques that involve the use of prestressed carbon fiber plate materials. In the present study, based on the anchorage characteristics of prestressed carbon FRP (CFRP) laminates, two anchorage systems (steel plate-type and clip-type) were developed. By making improvements to these two anchorage systems based on experimental and application results, an improved anchorage system was developed. The effectiveness of the improved anchorage system was evaluated by testing. In addition, the improved anchorage system was used in strengthening a real bridge. The anchorage efficiency and strengthening effect of the improved anchorage system were examined by a field test on the strengthened bridge.

2. Development of an Anchoring Technique That Uses Prestressing CFRP Laminates

Using a CFRP as the prestressed material to strengthen a structure has the following advantages [5, 13, 16–18]:

(1) Passive strengthening is turned into active strengthening.

(2) The high strength of the CFRP can be fully utilized in advance. A relatively large strain can be generated in the CFRP before it bears a load again, thereby effectively reducing or even eliminating the strain lag in CFRP laminates and consequently achieving a better strengthening effect.

(3) The reverse bending moment generated from the prestress can counteract part of the effect of the initial load, thereby increasing the load-carrying capacity during the operating stage as well as reducing the width or even closing the original cracks in the components and limiting the generation of new cracks. As a result, the stiffness of the components is increased, the deflection of the original components is decreased, and the performance of the components during the operating stage is improved.

(4) The deformation of carbon fibers consists of initial deformation and load-induced deformation. The shear deformation of the adhesive caused by the initial deformation and load-induced deformation of the carbon fibers are distributed at the two ends and in the midspan of the component, respectively. Because the shear deformation of the adhesive is more evenly distributed, the CFRP systems avoid bond failure.

Components requiring strengthening are prestressed (tensioned) using epoxy resin adhesive-coated carbon fibers to repair the deformation-induced and closed cracks in the beam. Then, carbon fiber laminates are bonded and anchored onto the components to increase their load-carrying capacity.

Based on this approach in conjunction with existing research on prestressing CFRP sheets [5], we developed a first-generation clip-type CFRP anchorage system by changing the bond-type anchorage device to a clip-type anchorage device and using high-strength bolts to apply a compression force. Tension loads provided by this CFRP anchorage system were limited to a few metric tons. The tension provided by this anchorage system could not be increased, and the CFRP utilization efficiency was still very low. In addition, because of the lateral compression effect of the clips on CFRP laminates, damage to CFRP laminates was not satisfactorily addressed. Furthermore, this anchorage system relied on an adhesive. Failure of the adhesive would lead to failure of this anchorage system. While this type of anchorage device can be easily fabricated and has a relatively low cost, its popularization is limited by its relatively low utilization efficiency. This fixed-type anchorage technique requires fixing the anchorage device in advance. Therefore, it is a type of improved bond-type anchorage device, and the stress cannot be accurately controlled when using it to tension a structure.

Based on the issues of the first-generation product during the application process, our research group developed an adjustable clip-type anchorage device (Figure 1). The second-generation product consists mainly of a special anchorage device, a fixing device, compressed bars, CFRP laminates, a special epoxy resin adhesive, and tensioning equipment.

3. Testing of the Performance Indices of the CFRP Laminate Anchorage System

The performance indices of the anchorage system were measured by tests required in the relevant design specifications and test standards (Table 1) after the anchorage system was completed. Table 2 lists the technical parameters of CFRP laminates used in the tests. The geometry parameters in Figure 2 are listed in Table 3.

Static loading test was performed as follows. All CFRP laminates had a strength ≥2,400 MPa. The anchorage efficiency coefficient was stable at >0.95, and the total strain was ≥1.2%. The stress on CFRP laminates was evenly distributed. In terms of the failure mode, a uniform failure of the fibers occurred across the entire fracture surface—a perfect failure mode (Figure 3). In Figure 4, the curves show a set of data (of OVM.CFRP 100-1.4) of anchorage characteristics during loading.

After 4,000,000 cycles of loading (upper stress limit: 66% of the standard tensile strength of CFRP laminates; stress range: 200 MPa), the anchorage efficiency coefficient was still 0.88 (Figure 5).

A fatigue test (stress range: 100 MPa; number of cycles of loading: 2,000,000) was also performed (Figure 6).

Relaxation test was performed as follows (Figure 7). A 1,000 h relaxation test revealed that CFRP laminates had a relaxation of 3.8% after 1,000 h.

Actual full-scale model beam test (Figure 8) was performed as follows. In March 2014, a strengthened 12 m-long beam was tested to determine its load-carrying capacity. After being strengthened, the load-carrying capacity of the beam increased by more than 60%. Long-term follow-up testing is currently underway.

Based on the test results, this CFRP strengthening system has the following technical advantages.

(1) The system is a mechanical anchorage system with a high anchorage efficiency coefficient (≥0.95) that can fully utilize the high-strength of CFRP laminates and thereby significantly increase the CFRP utilization efficiency. In addition, based on the results of the fatigue test (over 2,000,000 cycles of loading), the system can withstand high tensile loads, has high CFRP laminate utilization efficiency, and can meet large tonnage tensioning requirements. Furthermore, the maximum controllable tension can be set to $0.65\sigma_b$.

(2) The anchorage performance of the anchorage system mainly relies on the pretightening force of the clips. Because the anchorage system does not rely on an adhesive, it has outstanding reliability, safety, and durability and can be constructed in winter.

(3) The anchorage system can be quickly and easily constructed. The anchorage device and CFRP laminate assembly parts are manufactured in a factory. No wet construction is required, and heavy construction machinery is not needed. The construction process only requires a small space. Jacks can be removed once the installation and tensioning processes are completed. In short, this system requires minimal on-site construction space, auxiliary measures, and climate conditioning.

(4) Prestressing CFRP laminates can significantly increase the strength and stiffness of the reinforced concrete components. This process also effectively reduces the deflection of the structure, reduces the generation of new cracks, and closes existing cracks.

(5) The product has a small structural size and is light and thin. As a result, the product will add basically no weight to the original structure and will not affect the service space of the original structure. In addition, the anchorage system will leave few traces of strengthening.

4. Application Experiment in Bridge Strengthening

4.1. Test Content. To verify the effect of the anchorage system when used on actual engineering projects, a real bridge—the No. 1 Xiaojia Bridge—was selected for the strengthening test based on the existing cases involving the use of CFRP laminates for strengthening purposes [20–23]. The No. 1 Xiaojia Bridge is a river-crossing bridge located in a section of the Qingdao-Lanzhou Expressway (formerly the Jiaozhou Bay Expressway section) with a total length of 452.53 m, a combined width of 11.5 m $(0.5 + 10.25 + 0.75\ \mathrm{m})$, and an angle of 90°. The No. 1 Xiaojia Bridge was completed and opened for operation on November 31, 1994.

The No. 1 Xiaojia Bridge is composed of continuous prestressed concrete hollow slab beams and pot-type rubber bearings with a layout of 5×25.0 m. The fourth section is 75 m $(15.5 + 2 \times 22.0 + 15.5\ \mathrm{m})$ with a continuous prestressed concrete hollow slab beam and slab-type rubber bearings. Figure 9 shows the photographs of the No. 1 Xiaojia Bridge.

The test was conducted with the following objectives:

(1) To determine whether the actual mechanical conditions of the bridge structure met the design and specification requirements after it was strengthened with prestressing CFRP laminates.

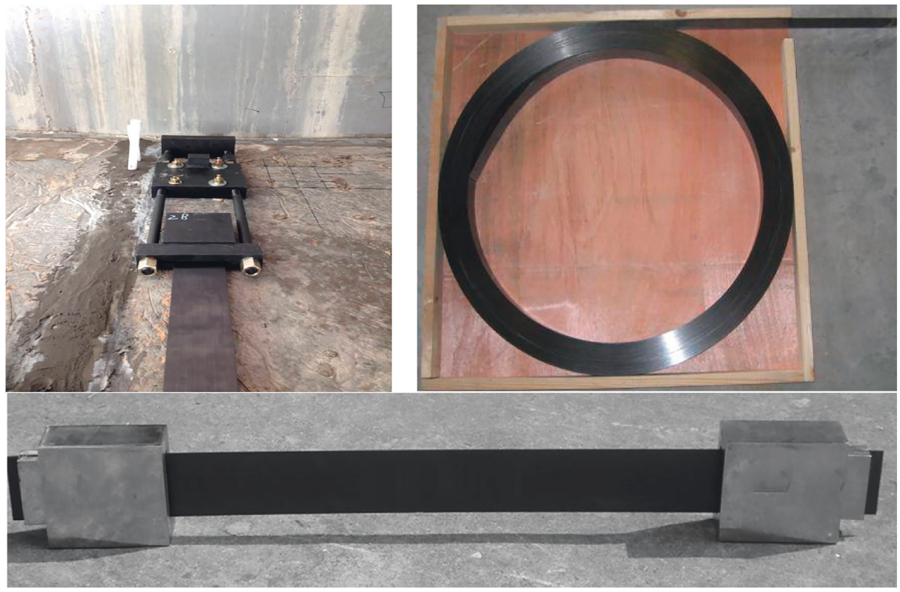

Figure 1: Clip-type anchorage system.

Table 1: Design and inspection standard for the system.

Standard number	Standard title
GB50367-2013	The design specification for concrete structure strengthening
GB50728-2011	Technical code for safety appraisal of engineering structural strengthening materials
JTG/T J22-2008	The design specification for highway and bridge strengthening
JTG/T J23-2008	The technical specification for highway and bridge strengthening construction
CECS146:2003	Technical specification for strengthening concrete structures with carbon fiber-reinforced polymer laminate [19]
T/T532-2004	Carbon fiber-reinforced polymer laminate for bridge structure
GB/T21490-2008	Carbon fiber sheet for strengthening and restoring structures
JG/T 166-2004	Resin for strengthening and restoring structures with fiber laminate
FIP1993	Recommendations for the acceptance of posttensioning systems
GB/T5028-93	Hydraulic jack for prestressing

Table 2: Technical parameters of carbon fiber laminate.

Type of CFRP	Specification (width × thickness) (mm)	Tensile strength (MPa)	Tensile modulus (GPa)	Extensibility (%)
OVM.CFP50-1.4	50 × 1.4	≥2400	≥160	≥1.4
OVM.CFP50-2.0	50 × 2.0	≥2400	≥160	≥1.4
OVM.CFP50-3.0	50 × 3.0	≥2400	≥160	≥1.4
OVM.CFP100-1.4	100 × 1.4	≥2400	≥160	≥1.4
OVM.CFP100-2.0	100 × 2.0	≥2400	≥160	≥1.4

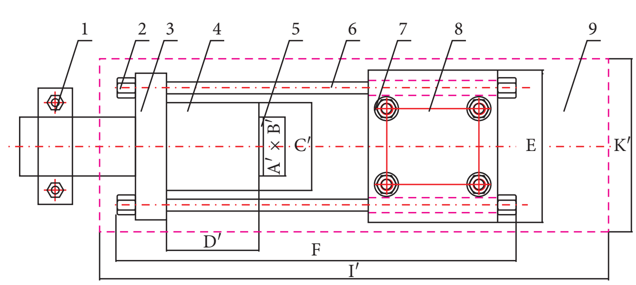

Figure 2: Anchor geometry parameters. 1, compress plate; 2, tensioning screw nut; 3, tensioning baffle; 4, carbon fiber anchor; 5, carbon fiber laminate; 6, pulling rod; 7, chemical anchors; 8, tensioning positioning device; 9, anchor sealing and anticorrosive material.

Table 3: Geometry parameters of anchor.

Type	$C' \times D' \times H$ (thickness)	$A' \times B'$	$E \times F$
OVM.CFP50-1.2	120 × 90 × 40	50 × 1.2	120 × 350
OVM.CFP50-1.4	120 × 90 × 40	50 × 1.4	120 × 350
OVM.CFP50-2.0	170 × 120 × 25	50 × 2.0	12 × 160
OVM.CFP100-1.2	150 × 150 × 55	100 × 1.2	24 × 300
OVM.CFP100-1.4	150 × 150 × 55	100 × 1.4	24 × 300
OVM.CFP100-2.0	150 × 150 × 55	100 × 2.0	24 × 300

(a)

(b)

Figure 3: Test photograph and failure mode of a CFRP laminate. (a) Strength test plan and (b) Failure mode of CFRP laminates.

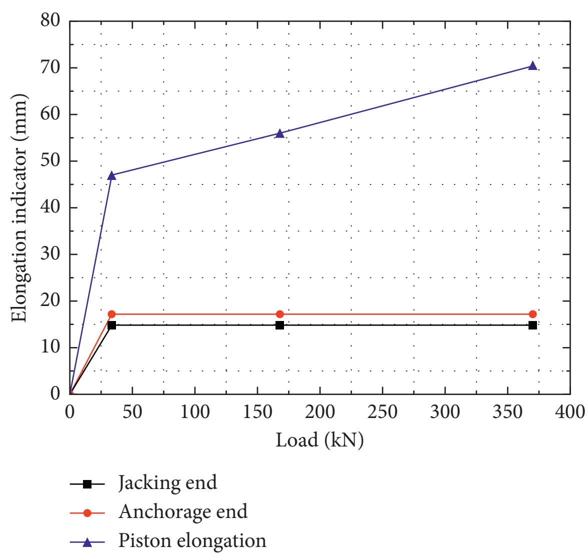

Figure 4: Elongation indicator curves with loading.

Figure 5: Anchorage efficiency test.

Figure 6: Fatigue test.

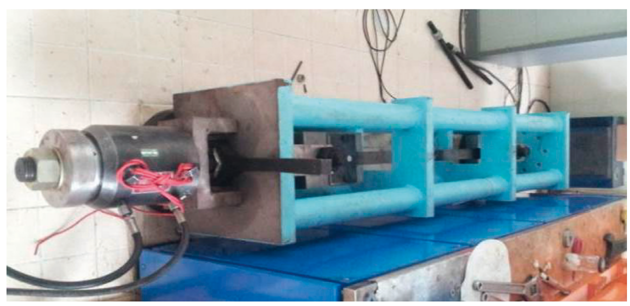

Figure 7: Relaxation test.

(a) (b)

Figure 8: Actual full-scale model beam test. (a) Loading plan and (b) location of CFRP laminates.

(a) (b)

Figure 9: Bridge photograph before and after strengthening. (a) Bridge bottom before strengthening and (b) bridge bottom after strengthening.

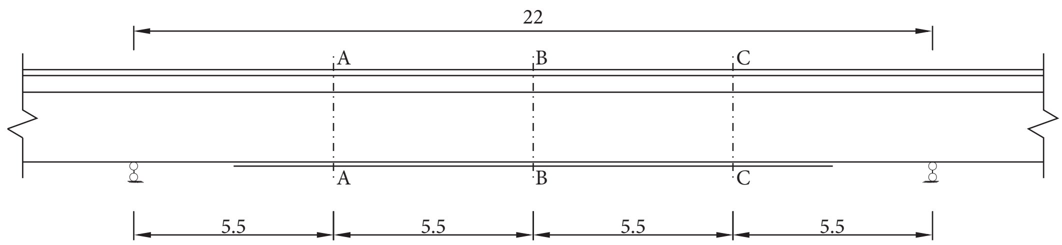

Figure 10: Cross section and longitudinal measurement point location (Unit: m).

Table 4: Strain increment of CFRP laminates before and after strengthening (unit: $\mu\varepsilon$).

Point	A-A section	B-B section	C-C section	A-A section	B-B section	C-C section
		Load case 1			Load case 2	
1	21	34	12	24	39	14
2	18	49	9	20	50	8
3	21	31	17	18	29	15
		Load case 3			Load case 4	
1	21	38	17	27	47	21
2	20	55	15	21	**57**	15
3	23	41	23	21	36	21
		Load case 5			Load case 6	
1	10	36	25	12	41	29
2	7	48	23	10	47	23
3	6	39	30	10	35	26

(2) To evaluate the overall bridge structure strengthening effect based on a comprehensive analysis of the data and phenomena observed during a field loading test, including measurements of the anchorage loss (retraction volume is measured when necessary), the elastic compression loss, and the effective prestress of CFRP laminates [13, 24].

(3) To examine the construction method for strengthening a bridge beam (prestressed concrete structure) with prestressing CFRP laminates and to make necessary adjustments based on the actual conditions.

(4) To determine the change in the stress in the beam after strengthening, to verify the strengthening effect of the application of a prestress, the performance of the adhesive (whether the deformations of CFRP laminates and the beam are compatible), and the reasonableness of the calculation model, to adjust and optimize the calculation model, and to provide a basis for further improvement of the theoretical calculation based on the field measurements of the key parameters of the anchorage system (e.g., anchorage loss, relaxation loss, elastic compression loss, and deformation compatibility, i.e., whether it conforms to the plane cross section hypothesis) [13, 16, 24, 25].

(5) To compare the cracking load before and after strengthening, estimate the ductility and load-carrying capacity of the beam after strengthening, and provide fundamental data for research on the stress relaxation of CFRP laminates and the long-term performance of the adhesive through continuous monitoring.

A loading test was conducted based on the relevant design documents, construction completion data, and data relevant to previous examinations, maintenance, and strengthening as well as technical specifications from China for highways and bridges [26–31].

4.2. Test and Loading Scheme. The bridge was loaded with an equivalent vehicle load based on the bridge design load standard. The loading test scheme (loading standard and method) was formulated based on the specification [26, 30, 32].

Based on the objectives of the loading test and strengthening scheme, the third span was selected as the test span because it was the only opening in the fourth section of the bridge ($15.5 + 2 \times 22.0 + 15.5$ m) on the right wing that was strengthened. Cross sections A-A, B-B, and C-C were selected for testing. The strain measurement points on each of the cross sections were numbered (Figure 10).

In the three cross section loading schemes, each cross section was subjected to a central and an eccentric loading for a total of 6 loading conditions. There are 6 load cases according to the loading arrangement at each of the cross sections (A-A, B-B, and C-C): (a) plane arrangement of vehicles, (b) longitudinal arrangement of vehicles, and (c) transversal arrangement of vehicles.

4.3. Test Results concerning Prestressing CFRP Laminates. Three strain measurement points were arranged on cross sections A-A, B-B, and C-C of each of three ordinary CFRP laminates. Table 4 lists the measurements of the strain in CFRP laminates during the loading test after strengthening. The maximum strain increment ($57\,\mu\varepsilon$) occurred at the midspan cross section under Load case 4.

Based on the test results, the effect of central versus eccentric loading conditions on the mechanical conditions of a CFRP laminate for the same cross section was relatively small. The properties of the adhesive for prestressing CFRP laminates were satisfactorily brought into full play. Overall, prestressing CFRP laminates and the bridge exhibited excellent operating performance.

5. Conclusions

(1) The special anchorage system developed for CFRP laminates could effectively increase the anchorage efficiency of CFRP laminates and help CFRP laminates achieve anchorage efficiency.

(2) The anchorage system allows full utilization of the properties of the CFRP with good fatigue life and relaxation. The test on the load-carrying capacity of a large-scale model beam showed that the load-carrying capacity of the beam increased by more than 60% after the beam was strengthened with the anchorage system developed in the present study.

(3) The field test of strengthening a real bridge showed that the stress distribution at the midspan cross section under each working condition after strengthening was reasonable.

(4) The loading test demonstrated that prestressing CFRP laminates exhibited excellent operating performance. The adhesive for CFRP laminates exhibited satisfactory bonding performance. The bearings exhibited reliable anchorage performance. The anchorage device underwent no retraction deformation. CFRP laminates incurred a small loss in prestress.

(5) During the static loading test, the residual deformation after the load applied by the vehicles was small regardless of whether the bridge was strengthened or not. The analysis before and after the bridge was strengthened showed that the expected bridge strengthening effect was achieved.

Data Availability

All the data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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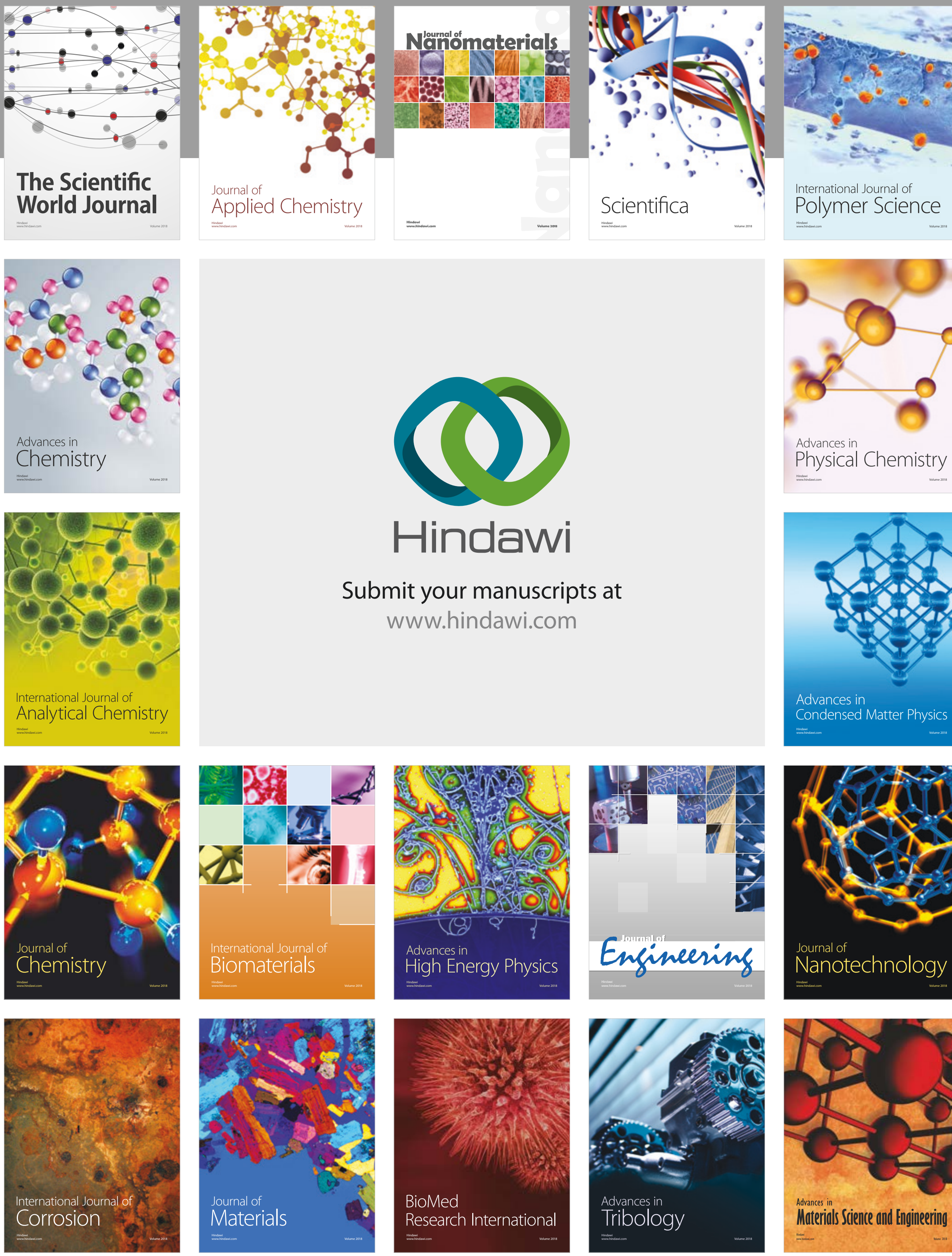
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