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Experimental Investigation of the Effect of Tensile Pre-Damage and Cyclic Loading on the Flexural Capacity of GFRP-Strengthened Steel Pipes under Dry and Wet Environmental Conditions

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ABSTRACT

In real operating conditions, strengthened tubes rarely experience simple loading states and may be simultaneously affected by initial deformation, cyclic loading, and environmental exposure. The interaction of these factors can introduce pre damage and alter the mechanical behavior and load bearing capacity of the structure during subsequent loading. This study experimentally examines the flexural behavior of steel tubes strengthened with glass fiber–epoxy composite after tensile pre damage, cyclic loading, and exposure to dry and marine environments. Two levels of initial tensile displacement equal to 10 millimeters and 30 millimeters and two levels of cyclic loading equal to 50 and 100 cycles were applied. The influence of environmental conditions was assessed by conditioning specimens in dry air and in simulated seawater for periods of 14, 25, and 40 days. The results indicate that an initial displacement of 30 millimeters significantly reduces flexural capacity, lowering the maximum flexural load from 18657.4 newtons to 10294.4 newtons. Under dry conditions, increasing the number of cycles decreases both cyclic load and flexural capacity, and increasing the initial displacement from 10 millimeters to 30 millimeters leads to a reduction of about 45 percent in flexural capacity. In contrast, for specimens with an initial displacement of 30 millimeters and 100 cycles, longer exposure to the marine environment increases flexural capacity from 5475.3 newtons to 20723.7 newtons, attributed to controlled softening of the epoxy matrix and completion of post curing. The findings show that in realistic service conditions, the flexural performance of strengthened tubes is strongly influenced by pre damage, loading history, and environmental exposure.

Keywords: Reinforced Steel Pipe, Bending, Tensile Pre-Damage, Cyclic Loading, Environmental Conditions

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بررسی تجربی اثر پیش‌آسیب کششی و بارگذاری چرخه‌ای بر ظرفیت خمشی لوله‌های فولادی تقویت‌شده با GFRP در شرایط محیطی خشک و مرطوب

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چکیده

در شرایط بهره‌برداری واقعی، لوله‌های تقویت‌شده معمولاً تحت یک حالت بارگذاری ساده و ایده‌آل قرار ندارند و ممکن است به‌طور همزمان در معرض تغییرشکل‌های اولیه، بارگذاری‌های چرخه‌ای و عوامل محیطی قرار گیرند. برهم‌کنش این عوامل می‌تواند موجب ایجاد پیش‌آسیب شده و رفتار مکانیکی و ظرفیت باربری سازه را در مراحل بعدی بارگذاری تغییر دهد. در این پژوهش، رفتار خمشی لوله‌های فولادی تقویت‌شده با کامپوزیت شیشه-اپوکسی پس از ایجاد پیش‌آسیب کششی، بارگذاری چرخه‌ای و قرارگیری در شرایط محیطی خشک و مرطوب به‌صورت تجربی بررسی شد. برای این منظور دو سطح جابجایی اولیه کششی ۱۰ و ۳۰ میلی‌متر و دو سطح بارگذاری چرخه‌ای ۵۰ و ۱۰۰ سیکل در نظر گرفته شد. همچنین اثر محیط با نگهداری نمونه‌ها در شرایط خشک و در محیط شبیه‌سازی آب دریا به مدت ۱۴، ۲۵ و ۴۰ روز ارزیابی شد. نتایج نشان داد اعمال جابجایی اولیه ۳۰ میلی‌متر موجب کاهش قابل توجه ظرفیت خمشی شده و نیروی خمشی بیشینه از ۱۸۶۵۷/۴ به ۱۰۲۹۴/۴ نیوتن کاهش یافته است. در شرایط خشک، افزایش تعداد سیکل‌ها باعث کاهش نیروی سیکل و ظرفیت خمشی شد و افزایش جابجایی اولیه از ۱۰ به ۳۰ میلی‌متر کاهش ظرفیت خمشی در حدود ۴۵ درصد را به همراه داشت. در مقابل، در نمونه‌های دارای جابجایی اولیه ۳۰ میلی‌متر و ۱۰۰ سیکل بارگذاری، افزایش مدت ماندگاری در محیط مرطوب موجب افزایش ظرفیت خمشی از ۵۴۷۵/۳ به ۲۰۷۲۳/۷ نیوتن شد که به نرم‌شوندگی کنترل‌شده ماتریس اپوکسی و تکمیل فرآیند پس‌پخت نسبت داده می‌شود. نتایج نشان می‌دهد در شرایط بهره‌برداری واقعی، عملکرد خمشی لوله‌های تقویت‌شده می‌تواند به‌طور قابل توجهی تحت تأثیر پیش‌آسیب، تاریخچه بارگذاری و شرایط محیطی قرار گیرد.

کلیدواژه‌ها: لوله فولادی تقویت‌شده، خمش، پیش‌آسیب کششی، بارگذاری چرخه‌ای، شرایط محیطی

نحوه ارجاع به این مقاله

بیرانوند رامین، انصاری مهدی، بررسی تجربی اثر پیش‌آسیب کششی و بارگذاری چرخه‌ای بر ظرفیت خمشی لوله‌های فولادی تقویت‌شده با GFRP در شرایط محیطی خشک و مرطوب، مهندسی مکانیک مدرس. *۹۸۸-۹۷۷:(۱۲)۲۶;۱۴۰۵*

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1- Introduction

Steel tubular structures and members are widely used in fluid transmission systems, offshore structures, piers, and many industrial infrastructures and play an important role in the safe performance of these systems [1]. These members are exposed to diverse and sometimes complex service conditions during their operational life, which may include corrosive environmental effects, variations in environmental conditions, and different types of loading. Among these loadings are repeated and bending loads caused by waves, vibrations, support settlements, or seabed deformations. Long-term exposure to such conditions can lead to corrosion, localized damage, and ultimately a gradual reduction in the load-carrying capacity of these structures [1–3]. This issue becomes particularly important in humid and marine environments, as the simultaneous presence of moisture and corrosive agents can accelerate material degradation and affect the long-term performance of the structure [4,5].

Under such conditions, the use of efficient methods for repairing and strengthening damaged steel members becomes particularly important. In recent years, the use of fiber-reinforced composite materials has attracted attention as one of the effective methods for repairing and strengthening damaged steel members. Due to their low weight, suitable strength, and high resistance to corrosion, these materials are considered an efficient option for restoring the load-carrying capacity and increasing the structural durability of steel members, and their application in strengthening pipelines and similar structural members has expanded [6] Among various repair methods, fiber-reinforced composite-based strengthening techniques have attracted widespread attention in recent years as one of the effective approaches [7].

Numerous studies have shown that the use of these strengthening systems, by creating a resistant layer around the damaged area, can improve stress distribution in the defect region and prevent stress concentration and damage propagation [8,9]. For this reason, the use of composite wraps can restore a significant portion of the lost capacity of damaged pipes and, in some cases, recover the structural performance to a state close to that of intact specimens [10]. Numerical and experimental investigations have also shown that the mechanical behavior of strengthened pipes can be predicted with acceptable accuracy using analytical models [10]. In this context, some studies have also focused on developing new concepts in the use of composite wraps to enhance the flexural resistance of steel members in corrosive environments and have shown that the use of wrapped GFRP layers can, in addition to providing protection against corrosion, significantly improve the flexural performance of steel members in marine environments [11]. Despite the significant advantages of composite strengthening systems, their performance depends on various factors. The properties of the filler material, the number and arrangement of composite layers, and the size and shape of the defect are among the parameters that can significantly affect the behavior of the repaired structure. For example, if the filler material fails at the early stages of loading, the role of the strengthening layers becomes limited, and the overall performance of the system will depend more on the defect size [7,9]. In addition, the orientation and stacking sequence of fibers in the composite layers can alter the stress distribution and the crack propagation path, and consequently affect the ultimate strength of the structure [8].

In recent years, efforts have also been made to improve the performance of materials used in the repair process. One of these approaches is the use of filler materials reinforced with nanoscale additives, which can enhance stress transfer between the steel pipe and the strengthening layers [12]. The use of composite patches in pipes with longitudinal cracks also reduces the stress intensity at the crack tip and increases the structural safety [13]. In studies related to the repair of composite structures, it has also been shown that the use of auxiliary materials such as stainless-steel wire meshes in the patch region can improve load transfer and prevent crack propagation by providing adequate continuity in the damaged area, such that the flexural load-carrying capacity of repaired specimens in some cases has even reached values close to or higher than those of intact specimens [14].

In addition to structural factors, environmental conditions also play an important role in the long-term performance of composite strengthening systems. Exposure of polymer composites to humid or marine environments may lead to moisture absorption, the formation of micro-damage in the matrix, and ultimately a reduction in certain mechanical properties such as stiffness and strength [4,5]. Therefore, evaluating the performance of strengthening systems under different environmental conditions, particularly dry and wet environments, is essential for understanding their actual behavior under service conditions. In addition, the mechanical behavior of the strengthening materials themselves can also be affected by the type of loading. For example, studies conducted on GFRP rebars have shown that cyclic loading with different frequencies can lead to a reduction in the elastic modulus and ultimate strength of these materials and may even alter their failure pattern [15].

From a structural perspective, the flexural behavior of pipelines is considered one of the important aspects of their performance. Studies have shown that the use of composite strengthening layers can increase the flexural stiffness and load-carrying capacity of damaged pipes and, in some cases, may also alter the failure mode of the structure [16,17]. In addition, investigations related to flexural fatigue have shown that the use of composite strengthening can reduce the crack growth rate and significantly increase the fatigue life of the structure [18–20]. Moreover, increasing the number of strengthening layers is generally associated with an increase in flexural strength and energy absorption capacity [21,22].

The performance of strengthened pipes under more complex loading conditions, such as cyclic loading or the combination of bending with other loading modes, has also been investigated. The results of these studies indicate that the use of composite strengthening can, in addition to increasing the structural stiffness, improve the resistance of the structure against crack propagation caused by repeated loadings [23,24]. Nonlinear numerical models have also been able to simulate the behavior of strengthened pipes under cyclic loading with reasonable accuracy [25]. Despite the significant progress in this field, many previous studies have mainly investigated the behavior of strengthened pipes under simple or static loading conditions, whereas under real service conditions these structures may be subjected to a combination of initial displacement, cyclic loading, and various environmental conditions before reaching the final loading state. Investigating these factors simultaneously can provide a more accurate understanding of the structural behavior of strengthened pipes.

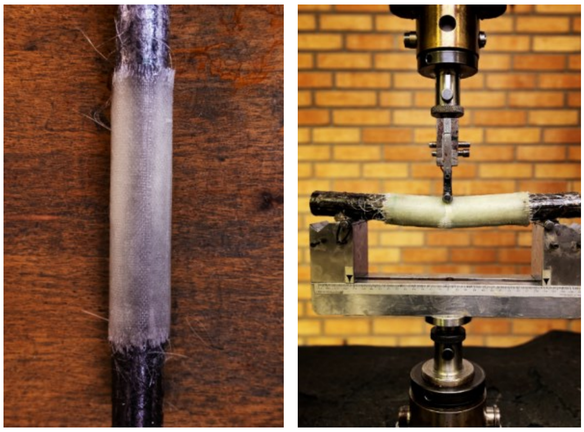
In spite of the studies conducted on strengthening steel members with composites, many investigations have paid limited attention to the simultaneous effects of factors such as mechanical pre-damage, cyclic loading, and environmental conditions, whereas under real service conditions these factors may act concurrently and influence the structural performance. Accordingly, in the present study, the flexural behavior of steel pipes strengthened with a composite wrap is experimentally investigated. In this study, the specimens were first subjected to tensile pre-displacement, followed by cyclic loading with a specified number of cycles. In addition, to evaluate the effect of environmental conditions, a portion of the specimens was kept in a simulated seawater environment and subsequently tested under bending. The aim of this research is to examine the simultaneous effects of pre-displacement, cyclic loading, and dry and wet environmental conditions on the flexural behavior, stiffness, and failure mode of composite-strengthened steel pipes.

2- Materials and Fabrication Method

In this study, seamless API-X42 steel pipes with a nominal diameter of 1 inch were used as the base elements. This type of pipe was selected due to its structural uniformity, the absence of welded regions, and stable mechanical behavior, ensuring that the influence of initial discontinuities on the test results was minimized. To strengthen the joint region, LR620 epoxy resin was used as the matrix material, and a woven E-glass fabric with an areal weight of 200 g/m² served as the reinforcing material. The resin and hardener were mixed according to the manufacturer's instructions at a weight ratio of 10 to 2 mL to obtain a uniform mixture. The purpose of specimen fabrication was to create an adhesive joint between two pipe segments and then strengthen this region with a composite wrap. For this purpose, two pipe segments with a length of 165 mm were first cut. The end surfaces of each segment were ground to eliminate cutting-induced irregularities and to ensure complete and uniform contact. Subsequently, the outer surface of the pipes in the reinforcement region was uniformly sanded to remove oxide layers and surface contaminants and to create adequate roughness for improved adhesion. The prepared surfaces were then cleaned with thinner followed by acetone to remove any residual grease or particles and to provide proper conditions for forming an effective bond.After surface preparation, the two pipe segments were aligned coaxially and bonded together using epoxy adhesive to form a continuous straight joint. The joint was considered the critical region, and composite reinforcement was applied to this area. First, a thin layer of resin was applied over the joint region, and then the E-glass fabric after complete impregnation with resin was wrapped layer by layer around the joint. The wrapped area included 75 mm from the end of the first pipe and 75 mm from the beginning of the second pipe, resulting in a total reinforced length of 150 mm. For all specimens, the number of composite layers was set to 15, which, considering the approximate thickness of each layer, produced a final wrap thickness of about 3 mm. The fabrication conditions, number of layers, and reinforcement dimensions were kept constant for all specimens to enable accurate comparison of the mechanical results.

3- Experimental Design

In this study, a targeted parametric experimental program was designed to evaluate the flexural behavior of composite-strengthened steel pipes after cyclic loading. In this program, the effects of three main variables—including the level of initial tensile displacement, the number of loading cycles, and the environmental conditions—were investigated with respect to the final flexural performance. After complete fabrication of the specimens, an initial controlled tensile displacement was applied at two levels, 10 and 30 mm, to simulate conditions equivalent to pre-damage or prestressing that may occur during real service, as this stage can generate residual stresses in the steel, stress concentration in the adhesive joint, initiation of micro-cracks in the composite layers, and changes in the initial stiffness of the system. The bending location was then selected so that it was exactly at the midpoint of the initial displacement zone; thus, for specimens with a 10-mm initial displacement, bending was applied at 5 mm, and for specimens with a 30-mm initial displacement, bending was applied at 15 mm. This selection was made because the greatest effects of pretensioning including residual stress distribution and potential damage are concentrated in the central region of the initial displacement, and applying bending at this location enables a more realistic assessment of the interaction between tensile pre-damage and flexural behavior. Figure 1-a shows the wrapped specimen, and Figure 1-b presents the specimen positioned for the bending test. After the pre-tensioning stage, the specimens were subjected to cyclic loading with a constant displacement amplitude of 2 mm. The number of cycles was selected at two levels, 50 and 100, to determine the influence of cyclic loading on stiffness degradation, reduction in load-carrying capacity, and changes in failure pattern. To examine the effect of corrosive environmental conditions, a portion of the specimens was stored in a simulated seawater environment for 14, 25, and 40 days after fabrication, allowing evaluation of moisture ingress and the potential weakening of the adhesive at the steel–composite interface. In addition to the cyclically loaded samples, two reference specimens were tested under bending without cyclic loading one without initial displacement and the other with a 30mm initial displacement to provide baseline behavior and isolate the effect of pre-displacement alone. Given the high cost of fabricating strengthened specimens and the time-consuming nature of cyclic and environmental conditioning, the experimental design was carried out as a targeted parametric study with a focus on analyzing behavioral mechanisms, stiffness variations, ultimate capacity, and failure modes. To organize the specimens and facilitate the interpretation of results, a three-part coding system was defined in which the first part, denoted by IDx, represents the initial tensile displacement in millimeters; the second part, denoted by Cy, represents the number of loading cycles; and the third part indicates the environmental condition, where D denotes dry conditions and SWt indicates exposure to the simulated seawater environment for t days. For example, the code ID30-C100-SW25 refers to a specimen with a 30-mm initial displacement, 100 loading cycles, and 25 days of seawater exposure prior to the final bending test, whereas specimens with the code C0 have no cyclic loading and are tested only under bending, serving as reference samples. Table 1 presents the experimental design.



(a) (b)

Fig. 1 a) Specimen wrapped with GFRP, and b) Specimen in the bending test

Table 1 Experimental Design of the Conducted Tests

Row	Specimen Code	Initial Tensile Displacement (mm)	Number of Cycles	Environment	Final Test
1	ID0-C0-D	0	0	Dry	Bending
2	ID30-C0-D	30	0	Dry	Bending
3	ID10-C50-D	10	50	Dry	Cyclic and Bending
4	ID10-C100-D	10	100	Dry	Cyclic and Bending
5	ID30-C50-D	30	50	Dry	Cyclic and Bending
6	ID30-C100-D	30	100	Dry	Cyclic and Bending
7	ID30-C100-SW14	30	100	Wet	Cyclic and Bending
8	ID30-C100-SW25	30	100	Wet	Cyclic and Bending
9	ID30-C100-SW40	30	100	Wet	Cyclic and Bending

4- Results and Discussion

In this section, the results obtained from the flexural and cyclic loading tests conducted on the composite-strengthened steel specimens are presented. The effects of the main experimental parameters including the level of tensile pre-displacement, the number of loading cycles, and the environmental conditions on the mechanical behavior and flexural capacity of the specimens are examined. The results are analyzed comparatively to identify the trends in cyclic force response and flexural capacity under varying conditions. In addition, the experimental data are illustrated through charts, and the key outcomes are summarized in Table 2 to enable an accurate comparison of the specimen performance.

4-1- PreTests

Bending pre-tests were conducted to determine the baseline behavior of the strengthened joint and to evaluate the independent effect of initial tensile displacement prior to entering the cyclic loading phase. In this stage, two specimens were investigated, both of which, after fabrication and completion of the composite wrapping process, were subjected to bending tests without any cyclic loading; the only difference was that one specimen had no initial tensile displacement, while the other was subjected to an initial displacement of 30 mm prior to the bending test. The results of these two pre-tests are presented simultaneously in Figure 2 to enable a direct comparison of their behavior. According to the results, the maximum bending force in the specimen without initial displacement was obtained as 18657.4 N, whereas this value decreased to 10294.4 N in the specimen with an initial displacement of 30 mm, indicating a significant reduction in load-bearing capacity of the joint. This reduction can be attributed to the introduction of pre-damage in the steel–adhesive–composite system. The application of initial tensile displacement leads to the development of residual stresses in the joint region, stress concentration at the interface, and the initiation of localized micro-cracks in the epoxy matrix. As a result, part of the stress transfer capacity between the steel pipe and the GFRP layers is reduced prior to the bending test, and the efficiency of the composite–steel load-sharing mechanism is weakened. In addition, the initial pre-strain may cause damage zones within the adhesive layer and reduce the cohesion between the components of the joint, which leads to a reduction in the effective stiffness of the system and accelerates the transition of the specimen into the nonlinear region during bending loading. From a mechanical perspective, the increase in initial displacement alters the stress distribution in the reinforced region and reduces the effective contribution of the composite layers to bending resistance; consequently, the specimen enters the damage propagation stage at lower loads and its ultimate capacity decreases. These results indicate that the presence of tensile pre-damage can significantly reduce the residual capacity of reinforced joints even before service loads are applied, and should therefore be carefully considered in the long-term performance assessment of such systems.

Table 2 Results Obtained for Pretests, Cyclic Loading, and Bending

Row	Specimen Code	Maximum Cyclic Force (N)	Maximum Bending Force (N)
1	ID0-C0-D	-	18657.4
2	ID30-C0-D	-	10294.4
3	ID10-C50-D	8130	1621.8
4	ID10-C100-D	4034.4	9049.8
5	ID30-C50-D	5401.7	15530.4
6	ID30-C100-D	3948.5	8387.6
7	ID30-C100-SW14	3893.3	5475.3
8	ID30-C100-SW25	6781.2	17057.2
9	ID30-C100-SW40	8547	20723.7

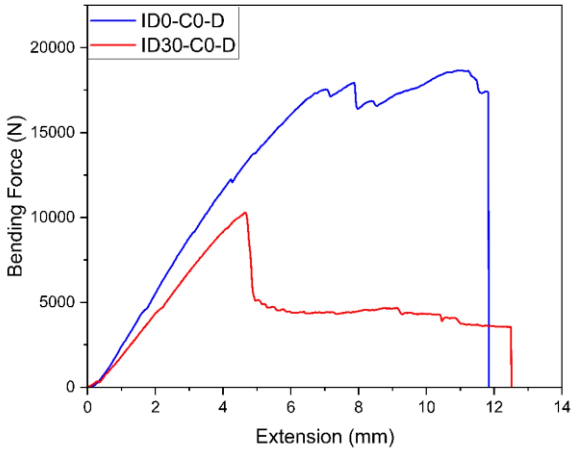


Fig. 2 Conducted PreTests

4-2- Cyclic Loading and Bending Curves with 50 Loading Cycles

In the investigation of specimens subjected to 50 loading cycles, the experiments were conducted at two levels of initial tensile displacement, namely 10 mm and 30 mm. In both cases, immediately after the completion of cyclic loading, a bending test was performed on the same specimen to evaluate the cumulative effect of pre-strain and cyclic loading without any time gap. The results of this section are presented in Figure 3. According to Figure 3(a), in the specimen with an initial displacement of 10 mm, the maximum force during cyclic loading was obtained as 8130 N, whereas this value decreased to 4034.4 N in the specimen with an initial displacement of 30 mm (Figure 3c). The bending test results also showed a similar trend, such that the bending capacity decreased from 16621.8 N in the 10 mm case (Figure 3b) to 9049.8 N in the 30 mm case (Figure 3d). These results indicate that increasing the initial tensile displacement plays a decisive role in reducing the residual strength of the joint after cyclic loading. A larger initial displacement leads to increased residual stresses in the joint region, stress concentration at the steel–adhesive–composite interface, and the initiation of localized damage in the epoxy matrix and interlaminar regions. Under such conditions, part of the energy absorption and stress transfer capacity of the system is consumed prior to cyclic loading, and the joint enters the repeated loading stage with an already pre-damaged state. Repeated loading over 50 cycles promotes the progressive growth of existing micro-cracks, reduces the effective adhesion at the interface, and degrades the mechanical integrity of the reinforced region. This phenomenon results in a reduction in the effective stiffness of the system and limits the contribution of the GFRP layers to the applied load. Consequently, both the load-carrying capacity during cyclic loading and the ultimate bending resistance are reduced. Moreover, the significant difference observed between the two levels of initial displacement indicates that the effect of tensile pre-damage on joint performance is more pronounced than the effect of 50 loading cycles, and the initial condition of the specimen plays a key role in determining its residual behavior. From an application perspective, these results suggest that in strengthened joints used in pipelines and structures subjected to repeated loading, initial deformations or pre-existing damage can significantly reduce the residual load-bearing capacity and adversely affect long-term structural performance.

4-3- Cyclic Loading and Bending Curves with 100 Loading Cycles

In Figures 4(a) to 4(d), the results of cyclic loading and bending tests for specimens subjected to 100 loading cycles are presented, respectively. In this stage, the experiments were conducted under the same conditions as the 50-cycle case, at two levels of initial tensile displacement, namely 10 mm and 30 mm. Immediately after the completion of cyclic loading, a bending test was performed on the same specimens to evaluate the cumulative effect of pre-damage and fatigue on the ultimate capacity of the joint. The results show that in the specimen with an initial displacement of 10 mm, the maximum force during cyclic loading was 5401.7 N (Figure 4a), whereas this value decreased to 3948.5 N in the specimen with an initial displacement of 30 mm (Figure 4c). The bending test results also exhibited a similar trend, such that the bending capacity decreased from 15530.4 N in the 10 mm case (Figure 4b) to 8387.6 N in the 30 mm case (Figure 4d). Comparison of these results with the specimens subjected to 50 loading cycles indicates that an increase in the number of cycles leads to a noticeable reduction in load-bearing capacity and applied load in both levels of initial displacement. This behavior suggests that with increasing cycle count, the gradually accumulated damage within different components of the joint has more opportunity to grow and propagate. Repeated loading leads to the development of micro-cracks in the epoxy matrix, degradation of the fiber–resin damaged state, leaving less capacity for additional damage accumulation during further cycling compared to the 10 mm specimens. In contrast, specimens with lower initial displacement start from a relatively less damaged condition, and thus the contribution of stages. It is noteworthy that the reduction in capacity due to the increase in cycle number is more pronounced in specimens with an initial displacement of 10 mm compared to those with 30 mm. This behavior can be attributed to the different initial damage levels in the two cases. In specimens with 30 mm initial displacement, a significant portion of damage in the form of residual stresses, matrix micro-cyclic loading to the overall degradation becomes more pronounced. Overall, the results for the 100-cycle tests indicate that the interaction between pre-strain and cyclic loading leads to a progressive reduction in effective stiffness, degradation of stress transfer capability, and a bonding, reduction of adhesion at the steel–adhesive–composite interface, and an increase in damaged regions within the reinforcing layers. Consequently, the efficiency of the stress transfer mechanism at the joint is reduced, and a portion of the system's load-carrying capacity is progressively lost. The observed reduction in stiffness can also be attributed to the accumulation of localized damage and the loss of structural integrity in the reinforced region, which causes the specimen to enter the nonlinear response regime at earlier loading cracks, and reduced interfacial adhesion has already been introduced prior to cyclic loading; therefore, the system is initially in a more decrease in the ultimate bending capacity of the joint. This highlights that in GFRP-strengthened systems subjected to repeated loading, residual performance assessment must consider not only the level of initial damage but also the loading history, as cumulative cyclic damage can significantly affect both load-bearing capacity and long-term durability of the system.

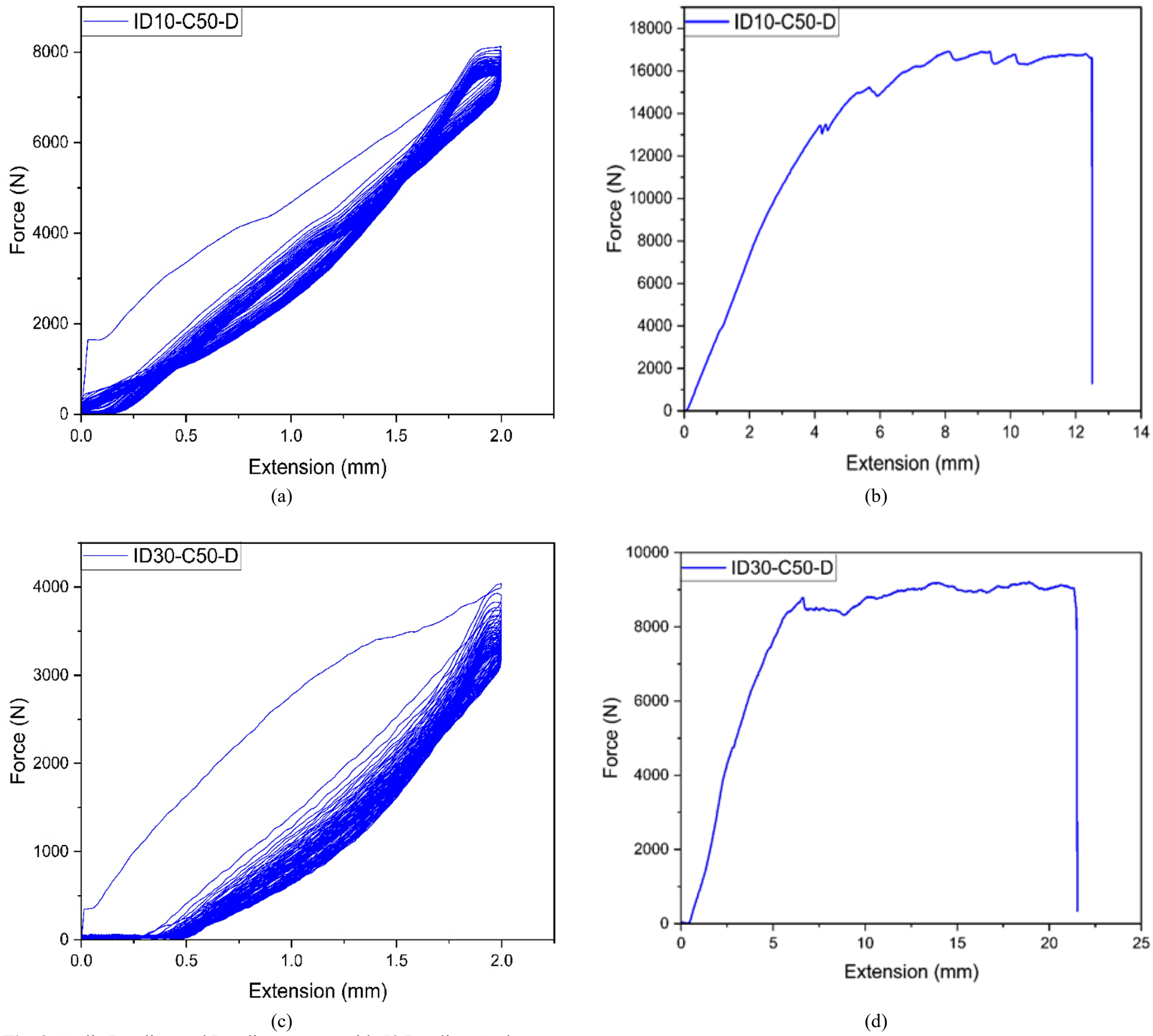
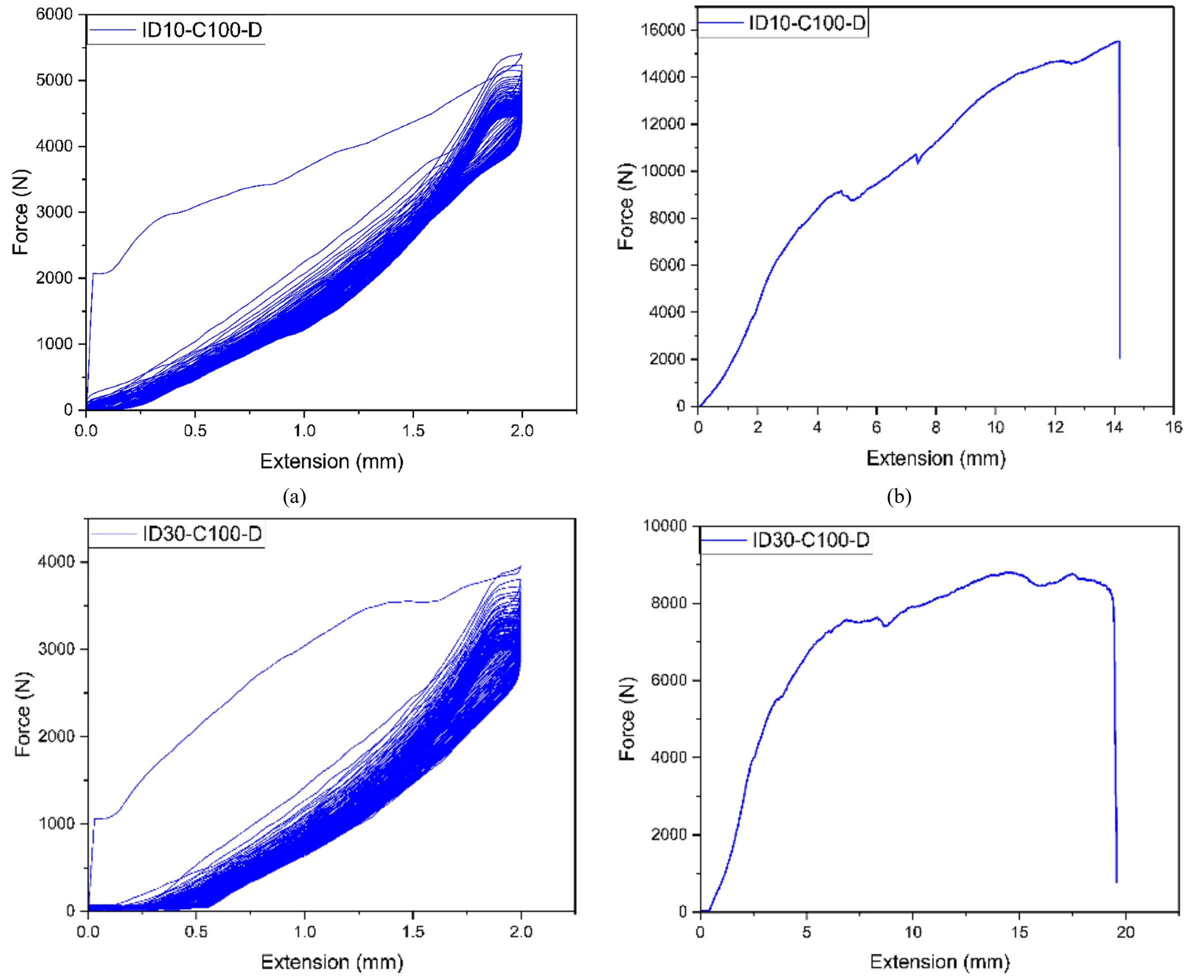


Fig. 3 Cyclic Loading and Bending Curves with 50 Loading Cycle

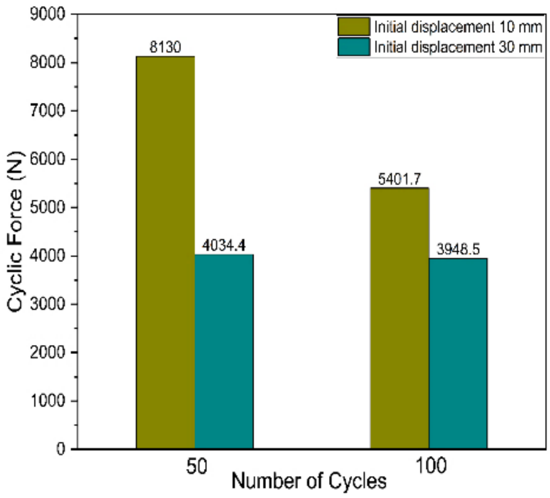


(a) (b) (c) (d)

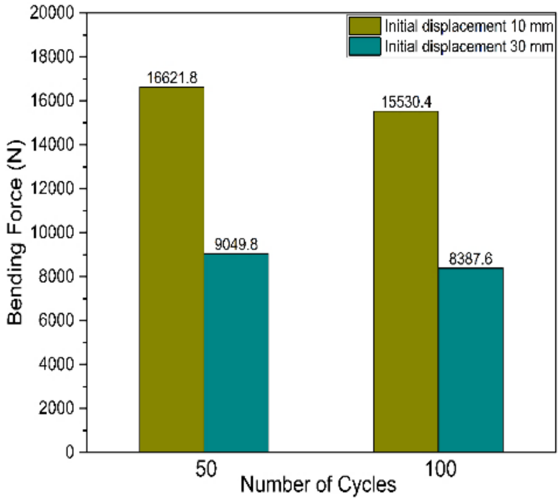
Fig. 4 Cyclic Loading and Bending Curves with 100 Loading Cycle

4-4- Cyclic Loading and Bending Bar Charts under Dry Environmental Conditions

In this section, the results of cyclic loading and bending tests under dry environmental conditions are presented comparatively in Figure 5. As can be observed, an increase in the number of cycles from 50 to 100 leads to a reduction in load-carrying capacity in both cyclic loading and bending stages. In the specimen with an initial displacement of 10 mm, the cyclic load decreased from 8130 N at 50 cycles to 5401.7 N at 100 cycles, corresponding to a reduction of approximately 33.5%. Under the same conditions, the bending load also decreased from 16621.8 N to 15530.4 N, indicating a reduction of about 6.6%. In the specimen with an initial displacement of 30 mm, the decrease in cyclic load from 4034.5 N at 50 cycles to 3948.5 N at 100 cycles was more limited, showing a reduction of about 2.1%, whereas the bending capacity decreased from 9049.8 N to 8387.6 N, corresponding to a reduction of about 7.3%. These results indicate that increasing the number of cycles has a more pronounced effect on capacity reduction in specimens with lower initial displacement (10 mm), while in specimens with higher initial displacement (30 mm), a significant portion of the damage has already been introduced during the pre-straining stage, and therefore the system becomes less sensitive to additional cyclic loading. From a mechanical perspective, repeated loading promotes the growth and coalescence of existing micro-cracks in the epoxy matrix, gradual degradation of the fiber–resin bonding, and deterioration of adhesion at the steel–adhesive–composite interface. This process leads to a reduction in stress transfer efficiency in the reinforced region and a decrease in the effective stiffness of the system. In contrast, in more severely pre-damaged specimens, the damage network is already partially formed, and the remaining capacity for further damage accumulation due to additional cycles is limited, resulting in a lower rate of degradation with increasing cycle count. Furthermore, comparison of the effect of increasing initial displacement from 10 to 30 mm shows that at 50 cycles, the cyclic load decreases by approximately 4095 N (about 50%), and the bending load decreases by about 7572 N (about 45%). At 100 cycles, the corresponding reductions are approximately 1453 N (about 26%) for cyclic load and 7142 N (about 46%) for bending capacity. These results indicate that the effect of tensile pre-damage on bending capacity reduction is more dominant than the effect of increasing the number of cycles, while cyclic loading mainly acts as an accelerating and aggravating factor for damage accumulation. Overall, the observed trends in bending results (as shown in Figure 6) suggest that the system response is more sensitive to the level of initial pre-damage than to the number of loading cycles; tensile pre-damage fundamentally alters the stress transfer mechanism and reduces the effective contribution of the GFRP layers to bending resistance, whereas cyclic loading primarily contributes to the growth and completion of pre-existing damage.



(a)



(b)

Fig. 5 Bar Charts for 50 and 100 Cycles a) Cyclic Loading and b) Bending

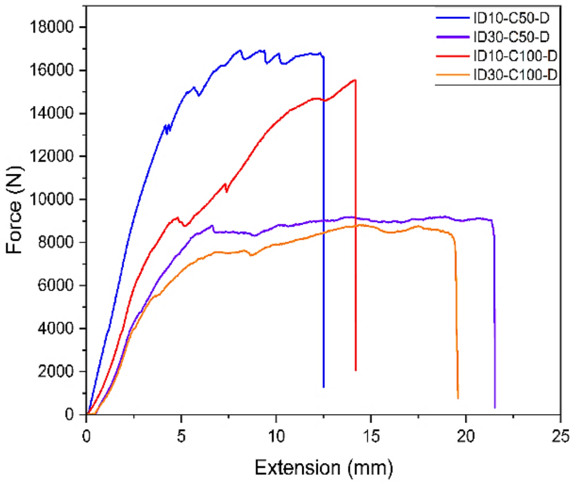


Fig. 6 Bending Test Curves for 50 and 100 Cycles

4-5- Cyclic Loading and Bending Curves under Wet Environmental Conditions

In the investigation of the effect of the wet environment, the initial tensile displacement and the number of loading cycles were kept constant at 30 mm and 100 cycles, respectively, in order to evaluate the effect of exposure time in a seawater-simulated environment without interference from other variables. This condition was selected because, under dry conditions, this combination resulted in a more critical mechanical response, and therefore it provides a suitable basis for assessing the system's sensitivity to environmental effects. The results presented in Figures 7(a) to 7(d), which respectively show the cyclic load and bending load of the 14, 25, and 40-day specimens, indicate an increasing trend in both parameters. Specifically, the cyclic load increased from 3893.7 N at 14 days (Figure 7a) to 6781.2 N at 25 days (Figure 7c) and 8547.3 N at 40 days (Figure 7c). Similarly, the bending load increased from 5475.3 N at 14 days (Figure 7b) to 17057.2 N at 25 days (Figure 7d), and then to 20723.7 N at 40 days (Figure 7d). This increasing behavior can be attributed to the simultaneous interaction of several phenomena within the epoxy matrix and the steel–adhesive–composite interface. In the initial immersion stage (14 days), moisture ingress induces physical changes in the resin, including limited plasticization and a gradual reduction in residual stresses induced by pre-damage. However, at the same time, the polymer network has not yet reached full stabilization, and the pre-existing micro-damage resulting from pre-straining and cyclic loading dominates the mechanical response. With increasing exposure time to 25 days, stress redistribution at the joint region and increased energy absorption capacity of the plasticized matrix improve stress distribution at the interface, thereby enhancing the effective contribution of the GFRP layers to bending resistance. At longer exposure times (40 days), in addition to the continuation of this trend, further stabilization of the epoxy network structure is also likely, leading to improved adhesion and enhanced stress transfer between the system components. Therefore, over the investigated time range, the combined effect of controlled matrix plasticization due to moisture absorption and gradual structural stabilization of the polymer network outweighs the potential adverse effects of moisture ingress at the interface, resulting in an overall increase in load-carrying capacity in both cyclic loading and bending stages. These results indicate that the environmental behavior of GFRP-strengthened systems is strongly governed by the interaction between resin physical changes and the initial damage state, and the effect of moisture cannot be considered purely detrimental.

4-6- Cyclic Loading and Bending Bar Charts under Wet Environmental Conditions

Comparison of the results of the wet specimens shows that, with increasing immersion time from 14 to 25 days and then to 40 days, both cyclic load and bending capacity increased in a stepwise manner. The cyclic load increased from 3893.7 N at 14 days to 2678.1 N at 25 days, indicating an increase of 2887.5 N, approximately 74%. Then, with further increase in time to 40 days, this value reached 8547 N, corresponding to an increase of 1769 N, about 26% compared to 25 days. In the bending test, a similar trend was observed; the bending capacity increased from 5475.3 N at 14 days to 17057.2 N at 25 days, showing a significant increase of 11581.9 N, approximately 212%, and then reached 20723.7 N at 40 days, which represents an additional increase of 3666.5 N, about 21% compared to 25 days. This increasing trend, which is shown in Figure 8(a) for cyclic loading and Figure 8(b) for bending, as well as in the cumulative bending results presented in Figure 9, indicates that the highest rate of performance improvement occurs between 14 and 25 days, after which the slope of increase becomes more moderate. This behavior can be attributed to the interaction of several mechanisms in the epoxy–steel–composite system. In the initial immersion stage (14 days), moisture ingress leads to physical changes in the epoxy matrix, including limited plasticization and a gradual reduction in residual stresses induced by pre-damage and cyclic loading, while the interfacial bond has not yet

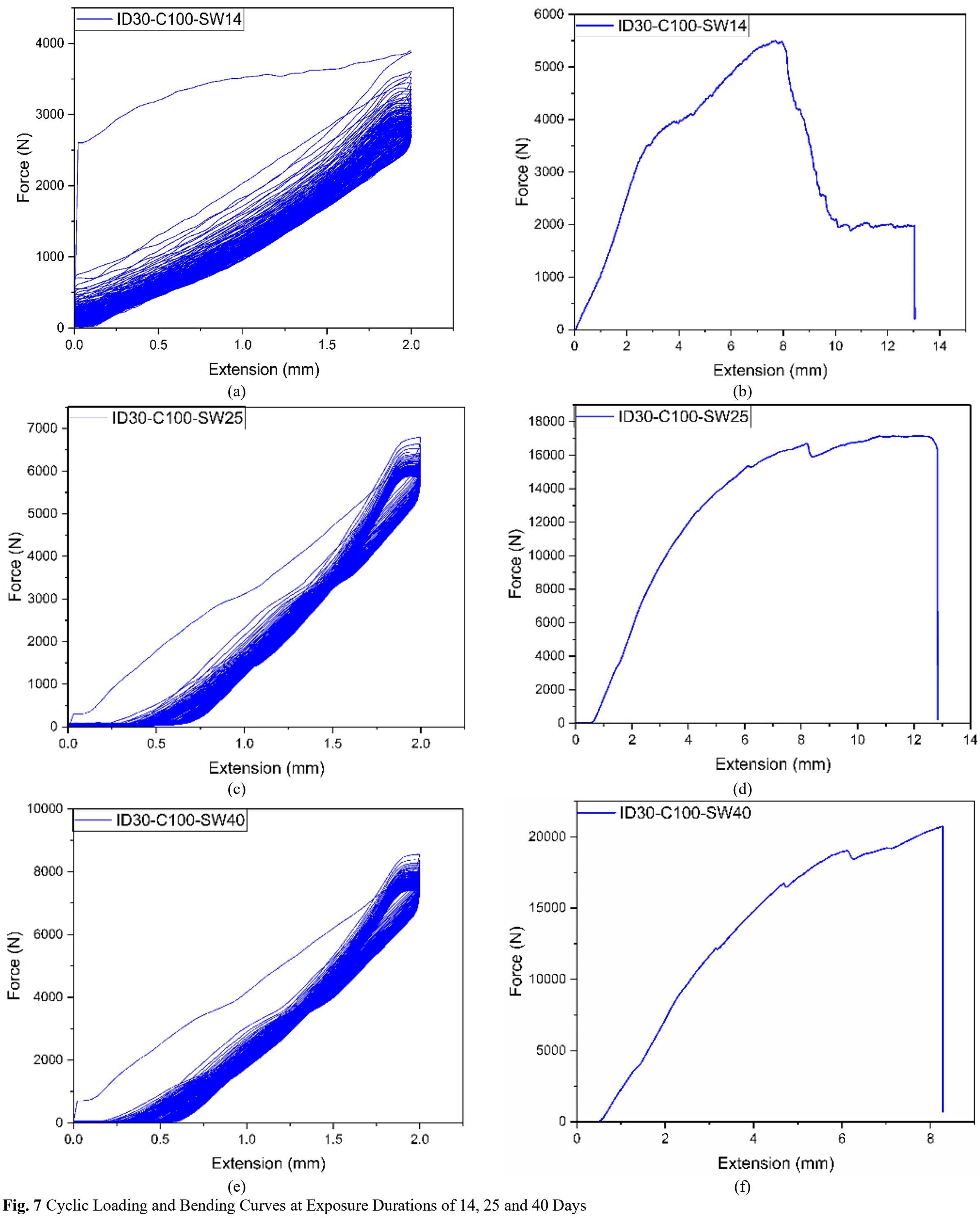
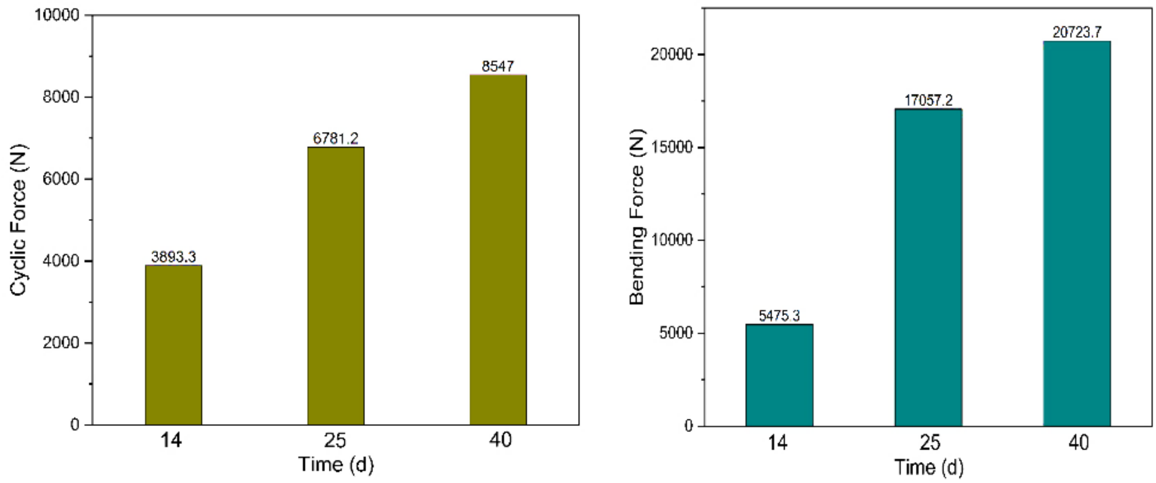


Fig. 7 Cyclic Loading and Bending Curves at Exposure Durations of 14, 25 and 40 Days

reached a stable state and the effect of initial damage remains dominant in the mechanical response. With increasing immersion time to 25 days, stress redistribution in the joint region and improved stress transfer conditions at the steel–adhesive–composite interface lead to a higher effective contribution of the GFRP layers in resisting bending and cyclic loads, resulting in a noticeable increase in load-bearing capacity. At 40 days, further stabilization of the polymer network structure contributes to improved adhesion and enhanced stress transfer capacity at the interface. Overall, over the investigated time range, the combined effect of controlled plasticization due to moisture absorption and gradual polymer network stabilization outweighs the potential adverse effects of moisture ingress at the interface, resulting in an increase in load-bearing capacity in both cyclic loading and bending stages.



(a) (b)

Fig. 8 Bar Charts at Exposure Durations of 14, 25, and 40 Days for a) Cyclic Loading and b) Bending

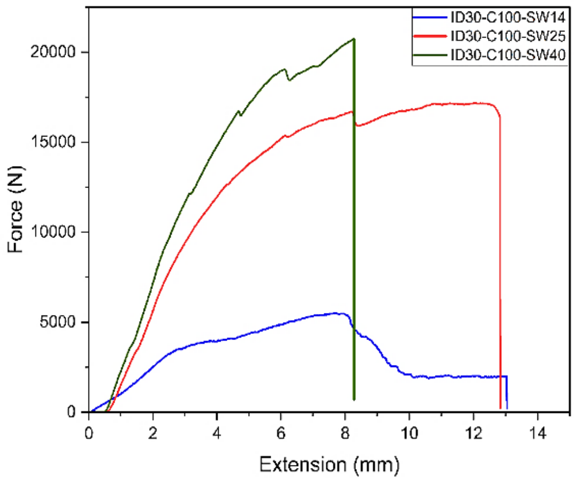


Fig. 9 Bending Test Curves at Exposure Durations of 14, 25 and 40 Days

5-Conclusion

In this study, the flexural behavior of a steel pipe reinforced with glass–epoxy composite was experimentally investigated after the application of initial tensile displacement, cyclic loading, and exposure to dry and wet environmental conditions. The main objective was to evaluate the simultaneous effects of initial displacement, number of loading cycles, and environmental conditions on the load-carrying capacity and mechanical performance of the strengthened system. Based on the experimental results, the most important findings of this study are as follows:

• The application of initial tensile displacement had a highly significant effect on reducing flexural capacity. Increasing the initial displacement to 30 mm reduced the maximum force from 18657.4 to 10294.4 N, indicating a substantial decrease in load-carrying capacity. This reduction is mainly attributed to the development of residual stresses, initiation of microcracks, and weakening of the interface between the steel and the composite layer.

• Increasing the number of loading cycles from 50 to 100 under dry conditions resulted in a reduction in the mechanical capacity of the specimens. At an initial displacement of 10 mm, the cyclic force decreased from 8130 to 5401.7 N, corresponding to a reduction of 33.5%. Under the same condition, the flexural capacity decreased from 16621.8 to 15530.4 N, representing a reduction of 1091.4 N, or about 6.6%. At an initial displacement of 30 mm, the reduction in cyclic force was much smaller, decreasing from 4034.4 to 3948.5 N. This change corresponds to a decrease of 85.9 N, or about 2.1%. In the same condition, the flexural capacity decreased from 9049.8 to 8387.6 N, representing a reduction of 662.2 N, or about 7.3%.

• Comparison of the effect of increasing the initial displacement from 10 to 30 mm showed that this parameter plays a dominant role in reducing capacity. At 50 cycles, the cyclic force decreased by 4095.6 N, corresponding to a reduction of about 50.4%, while the flexural capacity decreased by 7572 N, representing a reduction of about 45.5%. At 100 cycles, the cyclic force decreased by 1453.2 N, equivalent to a reduction of 26.9%, while the flexural capacity decreased by 7142.8 N, corresponding to a reduction of about 46%.

• Investigation of the wet environmental condition showed that increasing the exposure time from 14 to 25 days increased the cyclic force from 3893.3 to 6781.2 N, representing an increase of 2887.9 N, equivalent to approximately 74%. Increasing the immersion time from 25 to 40 days further increased this value to 8547 N, indicating an increase of 1765.8 N, or about 26% relative to the previous stage. The bending test results showed a similar trend; the flexural capacity increased from 5475.3 N at 14 days to 17057.2 N at 25 days, representing an increase of 11581.9 N, or approximately 212%. With further exposure up to 40 days, the flexural capacity reached 20723.7 N, showing an increase of 3666.5 N compared with 25 days, equivalent to about 21%. This improvement in performance under wet conditions is likely due to the post-curing phenomenon of the epoxy resin and improved bonding at the steel–composite interface in the presence of moisture during the early stages of immersion. However, it should be noted that this result is valid within the time range investigated in this study and cannot necessarily be generalized to longer immersion periods.

Overall, the results of this study indicate that initial tensile displacement is the most influential factor in reducing the bending capacity of GFRP-strengthened steel pipes, and its effect is more pronounced than that of the number of loading cycles. This can be explained by the fact that applying initial tensile displacement induces residual stresses, initiates micro-cracks in the epoxy matrix, and weakens the cohesion at the steel–adhesive–composite interface. As a result, part of the system's stress transfer capacity is consumed prior to the main loading stage, leading to a reduction in the effective structural stiffness. In contrast, cyclic loading primarily acts as an aggravating and propagating factor for pre-existing damage, and through the growth of micro-cracks and gradual degradation of fiber–resin integrity, it causes a progressive reduction in stiffness and load-bearing capacity. The results also showed that under wet environmental conditions and within the investigated time range, the load-bearing capacity of the specimens exhibited an increasing trend, contrary to the commonly expected behavior. This can be attributed to the interaction of physical and chemical phenomena such as controlled plasticization of the epoxy matrix, stress redistribution at the interface, and stabilization of the polymer network. These mechanisms enhanced stress transfer efficiency and increased the effective contribution of the GFRP layers in resisting bending loads over the studied period. In general, the findings demonstrate that the final performance of GFRP-strengthened steel pipes is governed by the complex and simultaneous interaction of mechanical pre-damage, cyclic loading history, and environmental conditions. Therefore, in the assessment of residual capacity and the design of GFRP-strengthened systems, the concurrent consideration of these three factors is essential for accurately predicting structural behavior under real service conditions.

Artificial Intelligence Statement: The authors used generative artificial intelligence (AI) tools exclusively for grammatical refinement and language polishing of the manuscript. Following the use of these tools, the authors reviewed and edited the content extensively to ensure accuracy and maintain the integrity of their original research.

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