Fatigue and Hygroscopic Performance of Injected Bolted Connectors in GFRP Sandwich Web Core Panels

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Abstract. The durability and fatigue performance of bridge components are critical factors in their long-term viability. This study investigates the experimental results of fatigue tests on injected Steel Reinforced Resin (iSRR) connectors, a promising connection technology for Glass Fibre Polymer (GFRP) composite decks in bridge construction. This research expands on previous work by examining the impact of environmental exposure on the cyclic performance of iSRR connectors. A total of twelve iSRR connectors were subjected to fatigue testing. Two connectors were exposed to outdoor conditions for one year, two connectors were fully submerged in water, and four connectors served as reference specimens without aging. The experiments aimed to evaluate the fatigue resistance and performance degradation of the connectors under varying environmental conditions. Additionally, the cyclic loading was conducted with varying R-ratios to understand the influence of load ratio on the fatigue life of the connectors. The specimens were loaded until failure, and a detailed analysis of the failure modes was conducted to determine the impact of environmental exposure and the load ratio on the failure characteristics of the connectors. The findings provide insights into the effects of environmental exposure on the fatigue performance of iSRR connectors and contribute to the development of more durable and reliable connection technologies for GFRP composite decks.

Keywords: Injected steel reinforced resin connectors · Fatigue · Water absorption · Experimental characterization

1 Introduction

The global road networks are expanding at a rapid pace, creating increasingly dense infrastructures. Beneath this growing network, however, lies a critical challenge: the highway bridges, which are vital to this system, are showing significant signs of fatigue and corrosion, struggling to meet the demands of modern traffic loads. Notably, the bridge decks are suffering from extensive wear and fatigue-related damage. One promising solution to address this challenge involves replacing the aging decks with composite sandwich web-core panels usually made with glass fibers, also known as Glass Fibre Reinforced Polymer (GFRP) panels. These panels are lightweight, resistant to fatigue

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and corrosion, and require minimal maintenance. Therefore, the introduction of GFRP panels in the highway bridge sector presents a viable step forward. However, integrating these advanced materials into existing bridge structures introduces a new challenge: how to reliably connect these new panels to the existing structural components.

To address this challenge, a novel type of connector, the injected Steel Reinforced Resin (iSRR) connector, has been developed and introduced in [1]. The iSRR connector combines standard steel rods or bolts with a surrounding injection of steel-reinforced resin (SRR), which consists of steel shot impregnated with a polymer resin. This injection material is placed into a large cylindrical hole in the composite deck, enveloping the mechanical connector, as shown in Fig. 1. This approach not only distributes bearing stresses more effectively but also eliminates slip due to the preloading of the steel connector against steel flanges. The design ensures that the GFRP laminate remains outside of the preload, entrusting the load transfer responsibilities to the SRR-encased steel connector, thus making this connection technology robust for bridge rehabilitation projects involving composite panels.

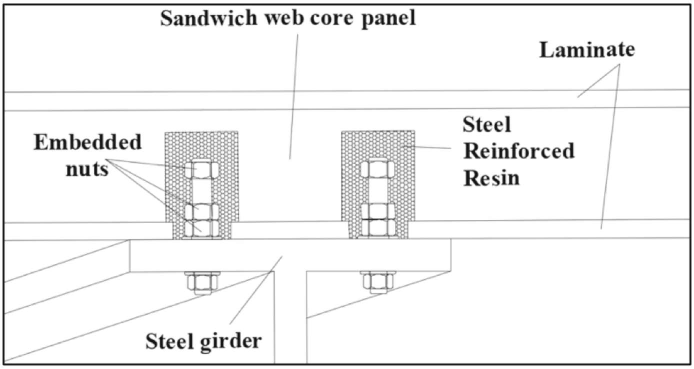


Fig. 1. Close-up view of iSRR bolted connections between composite deck panel and steel girder

In a previous study, iSRR connectors were tested at both room temperature (RT) and elevated temperature (ET), demonstrating promising fatigue resistance through the F-N curves, with slopes of −6.6 at RT and − 5.8 at ET [2]. These findings indicate robust performance, supporting their practical applicability in real-world scenarios. However, no information had previously been available regarding the effect of load ratio (R-ratio) and environmental factors, such as moisture. This conference paper is intended to fill these gaps, providing a more comprehensive understanding of iSRR connector behavior under diverse conditions.

2 Cyclic Experiments on Injected SRR Connectors

2.1 Specimens Details

The experimental setup and materials are the same as those described in a previous investigation of the iSRR connector's fatigue performance under room and elevated temperature conditions. The key dimensions of the test specimens and the configuration of the iSRR connectors are shown in Fig. 2a, while Fig. 3 presents the overall test setup used for cyclic loading and a close-up of the LVDT. For more comprehensive details regarding the materials, instrumentation, and boundary conditions, the reader is referred to [2]. Unlike the previous study, different R ratios will be applied in this investigation to assess their effect on the fatigue performance of the connectors and expand the understanding of load ratio influence on the fatigue behavior of the iSRR connectors. During testing, the panels were loaded in such a way that both top and bottom connectors were subjected to equivalent shear loading conditions. Care was taken to ensure symmetry in the setup, and no significant differences were observed in the load-displacement behavior or failure modes between top and bottom connectors. Therefore, the positional difference did not influence the test results in any measurable way.

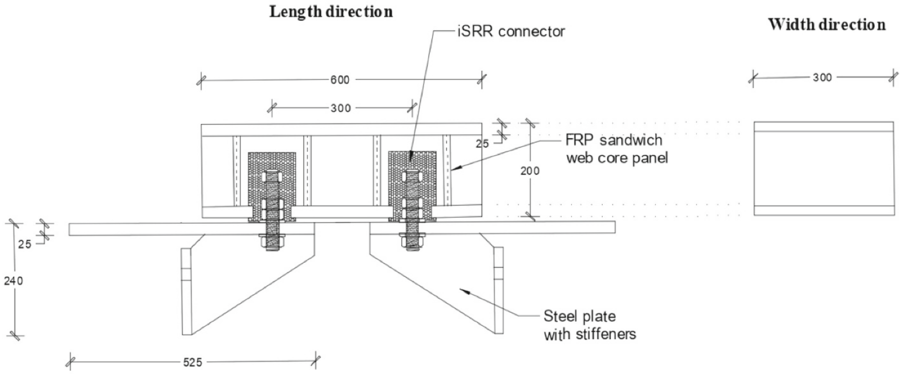
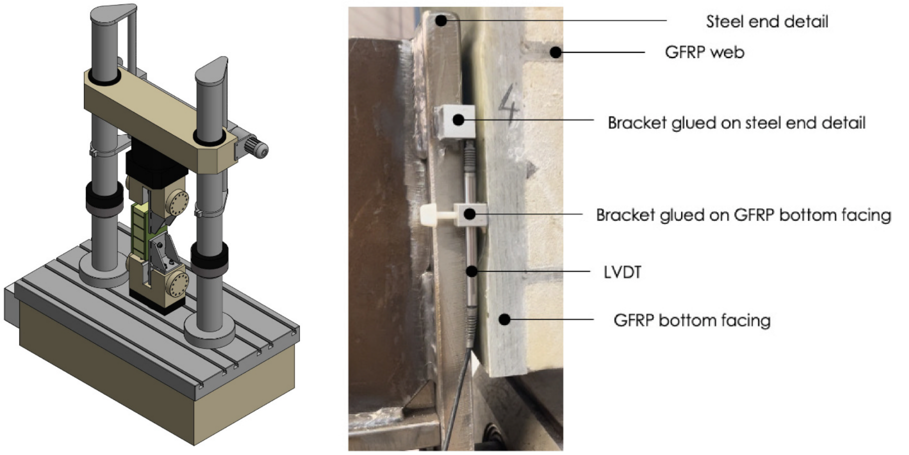


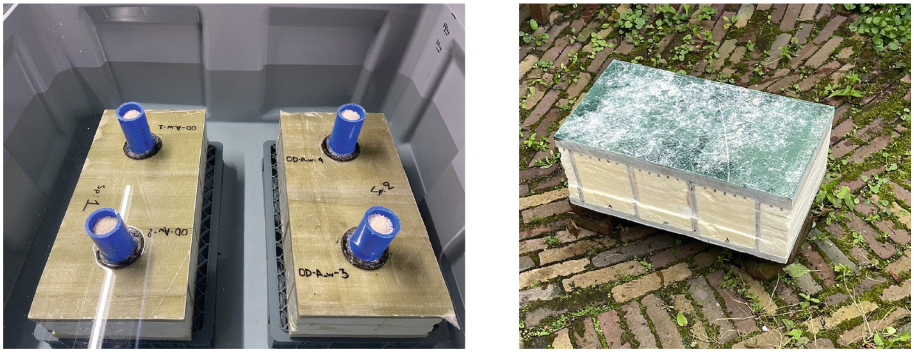
Fig. 2. Dimensions of the test configuration. Units are in mm [2]

Regarding the environmental exposure, four connectors are subjected to different environmental scenarios: two submerged in water and two exposed to outdoor conditions, each for a year, as shown in Fig. 4. The outdoor exposure of the panels took place in Delft, the Netherlands, between July 2023 and July 2024. During this period, the recorded air temperatures in Delft typically ranged between approximately −5 °C in winter and 30 °C in summer, based on data from the Royal Netherlands Meteorological Institute (KNMI). Therefore, the panels experienced an annual temperature variation of about 35 °C, representative of typical Dutch climate conditions. After this exposure, the connectors are tested under cyclic loading with a maximum load of 80 kN, and with the most detrimental R ratio that will be found in this study. To assess the impact of environmental exposure, these results are compared with the reference case of four connectors tested at room temperature, subjected to identical force ranges.



(a) Test setup (b) LVDT close up to measure FRP-steel relative displacement

Fig. 3. Details of testing



(a) Submerged connectors (b) Outdoors exposure

Fig. 4. iSRR connectors subjected to water exposure

2.2 Testing Matrix

A total of five specimens, comprising ten connectors, were prepared and tested, following a specific naming convention: X-YY-ZZ-E-D-C. The first character (X) represents the type of loading, which in this study is always “C” for cyclic loading. The ‘YY’ segment denotes the maximum applied load during the cyclic test. For fully reversed loading cases ($R = -1$), a single value is provided, while for non-fully reversed cases, both maximum and minimum loads are indicated. For instance, an R-ratio of 0.5 with a maximum load of 80 kN would be represented as 80_40. The letters (ZZ) denote the testing temperature, which remains constant at room temperature (RT) in this study. The letter (E) indicates the exposure condition: “U” for unaged, “S” for submerged in water, and “O” for outdoor exposure. The digit (D) refers to the specimen count for each parameter combination (X, YY, ZZ, E), which can be either 1 or 2. Lastly, the letter (C) designates the connector location within the panel, with "T" for top and "B" for bottom. A collection of all the parameters varying is presented in Table 1.

Table 1. Experimental testing matrix

Maximum load	R ratio	Environmental exposure	Number of connectors
40*	−1	No exposure	4
60*	−1	No exposure	4
80*	−1	No exposure	4
80	−0.5	No exposure	2
80	0.5	No exposure	2
80	0.1	No exposure	2
80	−1	Outdoors	2
80	−1	Submerged	2

*Results taken from [2]

The three conditions marked with an asterisk in Table 1 (40, 60, and 80 kN with R = −1) were previously tested and reported in [2]. They are included in the test matrix to provide a complete overview of the experimental program and to highlight the continuity and extension of the current work. However, to avoid redundancy, the results of these specific conditions are not discussed again in this manuscript.

3 Results and Discussion

3.1 Influence of R Ratio

An evaluation is performed on the effect of different load ratios on fatigue degradation, specifically focusing on the increase in additional displacement range. The displacement range increase is measured using Linear Variable Differential Transducers (LVDTs) that track the relative movement between the GFRP bottom facing and the steel end detail. The LVDTs are attached with their moving part positioned on the GFRP facing and their fixed bracket on the steel detail. By recording the change in relative displacement during each cycle, the total displacement range increase of the iSRR connectors can be evaluated, allowing for an accurate assessment of fatigue-related deformation over time.

The effect of the load ratio on the displacement range increase is shown in Fig. 4. In comparing the different load ratios (R = −0.5, R = 0.5, and R = 0.1), the connectors tested at R = −0.5 (green lines) consistently show the highest displacement range increase across the cycles, suggesting that they undergo accelerated stiffness degradation and earlier failure compared to the positive load ratios. In contrast, the connectors tested at R = 0.5 (blue lines) exhibit minimal displacement range increase, maintaining a stable behavior even after prolonged cycling, indicating that this ratio is the least detrimental in terms of fatigue performance. Meanwhile, the connectors tested at R = 0.1 (red lines) fall in between, showing a moderate displacement range increase, but not as significant as the R = −0.5 cases.

Based on Fig. 5, an assessment is made of the connectors tested under load ratios R = −1 (gray lines) and R = −0.5 (green lines). It is expected that the connectors subjected to R = −1 would experience more severe fatigue damage compared to those under R = −0.5, as fully reversed loading typically induces greater stress variations. This load ratio has been previously identified in the literature as leading to the highest degradation rate [1]. However, due to malfunctioning LVDTs, reliable initial measurements were not recorded for the connectors tested at R = −0.5, resulting in uncertainties in the displacement data. Consequently, with the current data and post-processing, it is not possible to draw definitive conclusions regarding the comparative severity of the two load ratios.

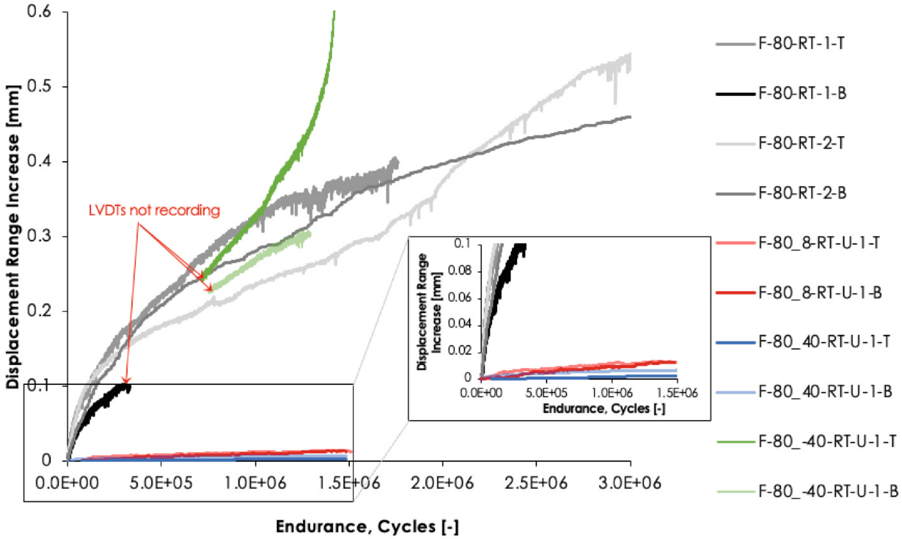


Fig. 5. Displacement range increase of different R ratios at maximum load level of 80 kN

For a more robust evaluation, the extrapolation methods described in [2] are used to create Fig. 6 which illustrates the log-log relationship between the number of cycles (x-axis) and the maximum applied force (y-axis) for four different R-values: −1, −0.5, 0.1, and 0.5. All the curves start at 120 kN on the y-axis, which corresponds to the slip resistance of the iSRR connectors. This is because if the connector were subjected to a maximum force of 120 kN, slip would occur almost immediately, and the 0.3 mm displacement range increase would be reached within the first cycle. This starting point serves to illustrate the limiting condition of the iSRR connector’s performance, with lower applied forces requiring more cycles to reach the failure threshold. Additionally, results from [2] are utilized to provide more data for accurate estimation for R = −1.

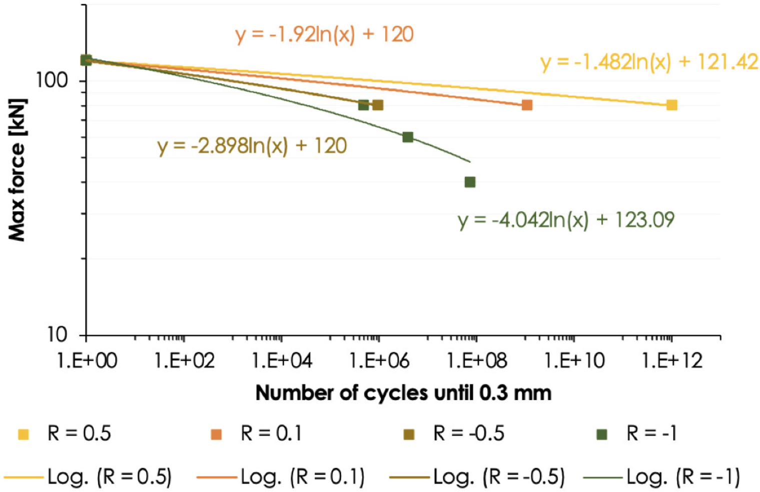


Fig. 6. Influence of R-ratio on the fatigue life of the connectors under shear loading

The slope of the curves demonstrates how the fatigue life decreases as the maximum applied force increases, with the load ratio influencing the rate of this reduction, indicating the influence of different load ratios on the rate of fatigue degradation. As expected, the $R = -1$ curve exhibits the steepest slope, suggesting that under fully reversed loading conditions, the connectors experience the most rapid degradation in their fatigue life. This behavior is attributed to the reversal of stress in each cycle, which intensifies fatigue damage by subjecting it to alternating compressive and tensile stresses. Consequently, the fully reversed load ratio induces greater damage accumulation compared to other load ratios, where the stress amplitudes are lower.

Conversely, the curves for positive load ratios, particularly R = 0.5, show much gentler slopes, implying that these loading conditions impose less severe fatigue damage on the connectors. The flatter the slope, the greater the number of cycles the connectors can endure before reaching the failure threshold of 0.3 mm displacement range increase. This aligns with the expectation that lower amplitude loading cycles (higher R-values) allow for an extended fatigue life.

3.2 Influence of Environmental Exposure

The fatigue performance of iSRR connectors is evaluated after one year of environmental exposure to investigate the effects of prolonged outdoor and submerged conditions. These connectors are tested under cyclic loading of ±80 kN since $R = -1$ is identified as the most detrimental condition for fatigue performance in the previous section.

3.2.1 Stiffness Degradation

The relative stiffness degradation of iSRR connectors subjected to different environmental conditions over their fatigue life is presented in Fig. 7. The submerged connectors (red lines) exhibit rapid and pronounced stiffness degradation, reaching failure considerably earlier than both the outdoor-aged connectors and the reference specimens. This early failure suggests a critical vulnerability to prolonged water exposure, likely due to mechanisms such as the swelling of the resin matrix, corrosion of the embedded steel particles, or a weakening of the bond between the SRR piece and the composite component.

The connectors exposed to outdoor conditions (blue lines) demonstrate a relative stiffness degradation profile similar to that of the reference connectors (black and grey lines) until late in the test, suggesting that typical outdoor conditions have a less significant impact on the fatigue performance compared to direct submersion.

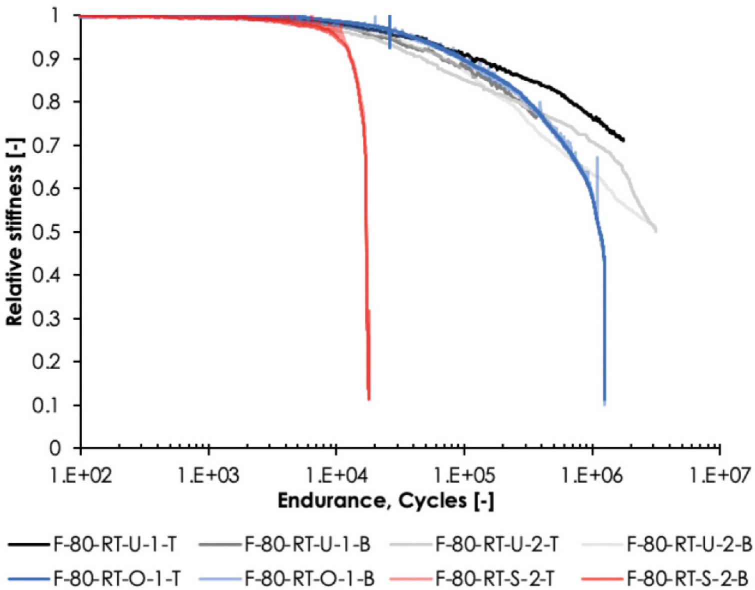


Fig. 7. Relative stiffness of iSRR connector at different cyclic load levels under different environmental exposures

3.2.2 Fatigue Life under Various Exposure Conditions

The fatigue life extrapolation for iSRR connectors subjected to one year of environmental aging is extrapolated based on the two methods presented in [2]. Figure 8 displays the displacement range increase of iSRR connectors tested at a consistent load level of ±80 kN. Interestingly, the connectors aged outdoors exhibit a displacement range increase that is very similar to the reference connectors tested at room temperature. This suggests that the outdoor exposure, while slightly affecting the connector performance, did not drastically reduce fatigue resistance compared to the non-aged connectors. Both the blue and the black lines show a more gradual increase in displacement range compared to the submerged connectors. However, between the reference (blue) and the outdoor-aged (black) connectors, the reference connectors seem to perform slightly better, displaying a slightly slower rate of displacement increase, indicating greater resistance to fatigue.

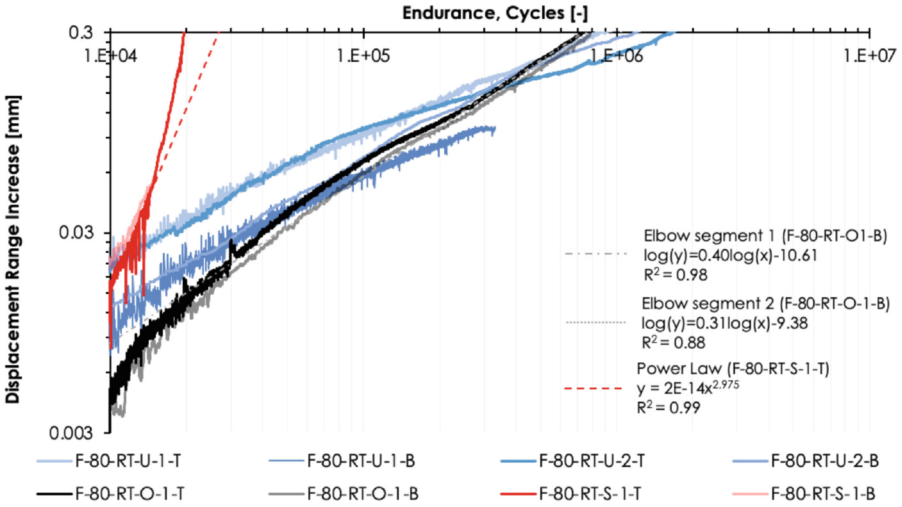


Fig. 8. Recorded connectors' displacement range increase in logarithmic scale axes under different environmental exposure conditions.

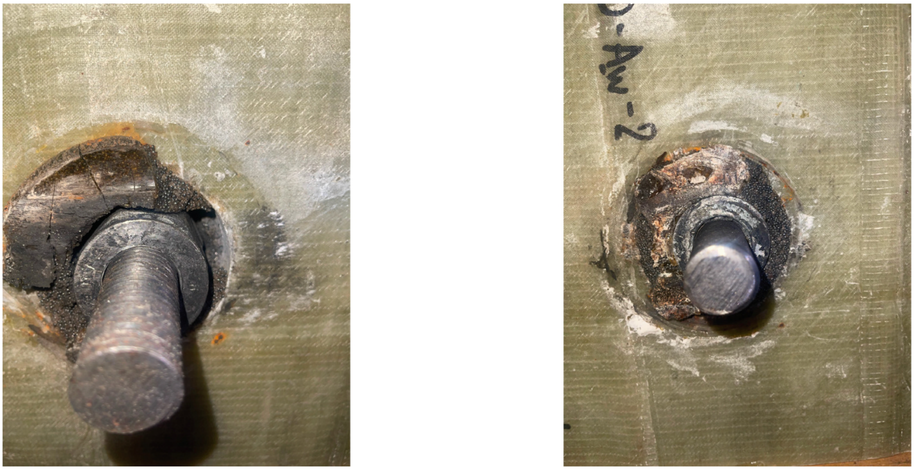
On the other hand, the submerged (red) connectors display the fastest displacement range increase, indicating accelerated stiffness degradation and earlier failure compared to both the outdoor-aged and the reference connectors. This implies that water exposure has a more detrimental impact on the fatigue performance of the connectors, leading to a significant reduction in fatigue life. The submerged connectors reach the 0.3 mm failure criterion much earlier, around $2 \cdot 10^4$ cycles, whereas the outdoor-aged connectors and the reference connectors demonstrate a more gradual progression, reaching the 0.3 mm failure criterion closer to $7.5 \cdot 10^5$ cycles.

These results highlight that outdoor exposure has a less drastic effect on the fatigue performance compared to submersion. Importantly, considering the intended application of these connectors in bridge structures, where they will always be in non-submerged conditions, the outdoor exposure results are particularly relevant. The study involving submerged conditions was conducted to evaluate the worst-case scenario, ensuring comprehensive safety margins. Given the promising results observed in the outdoor-aged connectors, it is evident that the iSRR connectors exhibit sufficient resilience for bridge environments, where occasional wetting due to rain or moisture is expected, but continuous submersion is not.

3.2.3 Failure Modes of Injected SRR Connector

Notably, the failure mode of the submerged connectors is characterized by debonding between the SRR piece and the GFRP facing, along with the crushing of SRR material beneath the embedded nuts. It is also important to keep in mind that this type of submerged connectors are not realistic considering the presence of free edges in the GFRP deck that accelerates the water uptake thereby eventually causing damage to the material and the interfaces. The presence of free edges is a result of cutting the GFRP deck in the required dimension and if eliminated can help minimize the water uptake.

The failure mode for the outdoor-aged connectors, similar to that of the submerged connectors, involves debonding between the SRR piece and the GFRP facing, as well as crushing of the SRR material beneath the embedded nuts as shown in Fig. 9(a). However, the extent and timing of this damage are less severe and occur much later compared to the submerged connectors, which implies that outdoor exposure does not exert the same level of stress on the connectors' internal bonding as direct water immersion.



(a) S-80-RT-S-1-T (b) S-80-RT-S-1-B

Fig. 9. Failure mode of iSRR connectors under cyclic loading after water submersion

Figure 10 shows the condition of the composite deck with iSRR connectors after one year of submersion in water. The black lines indicate the visible extent of water ingress into the composite material. The significant weight gain observed during the submersion period suggests a high level of water absorption, likely affecting the interface between the SRR and the GFRP facing. This water penetration could have weakened the adhesive bond and compromised the structural integrity of the interface, potentially contributing to the observed failure modes under subsequent loading.

(a) Front view (b) Behind view

Fig. 10. Condition of composite deck with iSRR connectors after a year of water submersion

4 Conclusions

This study assessed the fatigue and hygrothermal performance of iSRR connectors used in GFRP sandwich web core panels. The experimental results demonstrated that the iSRR connectors have promising fatigue resistance under cyclic loading, even when subjected to various environmental conditions, including outdoor exposure and full submersion in water. The outdoor-aged connectors exhibited fatigue life comparable to that of unaged reference connectors, suggesting the robust nature of the iSRR technology for practical bridge applications, where occasional wetting is anticipated. However, full submersion significantly reduced fatigue resistance, highlighting vulnerabilities in water-immersed environments.

The impact of different load ratios was also explored, revealing that the load ratio of −0.5 significantly accelerates stiffness degradation and reduces fatigue life, while R = 0.5 provides the least detrimental effect. The R ratio of −1, previously identified as highly damaging, confirmed its adverse impact during these experiments, exhibiting the steepest F-N slope. The connectors' stiffness degraded more rapidly when subjected to elevated temperature or prolonged water exposure, with submerged conditions leading to more pronounced degradation.

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