Research on the Seismic Performance of Highly Durable Concrete Structures with Corrosion-resistant Reinforcing Steel Materials

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Abstract. The combination of high durability concrete and GFRP reinforcement for infrastructure construction in the South China Sea can meet its durability requirements under high temperature, high humidity, high salt spray and high radiation environment. Due to the frequent seismic activities in the South China Sea, it is imperative to study the bearing capacity and seismic performance of GFRP reinforced high-durability concrete components and structures. The authors first analyzed the load-bearing performance of GFRP reinforced highly durable concrete beams and established the correction formula for its load-bearing capacity calculation based on the research results. Then the seismic performance of the GFRP reinforced high durability concrete structural members is studied. The seismic damage of the new structure and components is studied by analyzing the hysteresis curve, skeleton curve, stiffness degradation and other parameters. The time course curves and inter-layer displacement angles of GFRP reinforced high durable concrete structure are studied by adjusting the reinforcement type and concrete type, and finally the seismic performance of GFRP reinforced high durable concrete structure is obtained.

1. Introduction
With the increasing scarcity of land resources in China, marine development will be of great strategic significance to the future development of China. The high temperature, high humidity, high salt spray and high radiation environment of the South China Sea islands pose a great challenge to the durability of building materials, and ordinary reinforced concrete materials cannot support the durability of the building requirements. The team prepared highly durable concrete by adjusting the content of slag admixtures (silica powder, ultrafine slag, high quality fly ash), basalt fibers, and polystyrene fibers through orthogonal tests. Combined with GFRP reinforcement with high tensile strength and good corrosion resistance, the concrete was used as an infrastructure construction material in the South China Sea region to meet the requirements for structural corrosion resistance under extreme hot and humid environments.

Due to the relative motion and interaction of the lithospheric plates along the boundaries of the reefs and latitudes in the South China Sea, earthquakes occur frequently in the South China Sea, and are distributed around Taiwan South and the Philippines[1]. Since 2000, there have been 26 earthquakes of Magnitude 6 or higher in this seismic zone, including two earthquakes of Magnitude 7 or higher at a depth of 10 km, with an average of one earthquake of Magnitude 7 or higher occurring every 10 years. The choice of building materials and structural forms is of paramount importance when carrying out construction work in the South China Sea. High-durability concrete and GFRP reinforcement are the building materials suitable for building structures in the harsh marine environment of the South China Sea and can meet the requirements of building durability. Under
comprehensive consideration, this paper takes reinforced concrete structural members as the main form and proposes the correction formula for calculating the load capacity of GFRP reinforced high durability concrete members through finite element analysis, and carries out the research on the seismic performance of GFRP reinforced high durability concrete structural members.

2. Mechanical Properties Analysis of Highly Durable Concrete Members with Corrosion-Resistant Reinforcement

2.1 Constructs and Modeling Parameters

In order to study the mechanical properties of highly durable concrete specimens with corrosion-resistant reinforcement, finite element simulation analysis of the bending of the positive cross-section of balanced-reinforced beam with different combinations of reinforcement and concrete is carried out. The high durability concrete structure model is taken from the test data of Fu Qiang[2]. The GFRP reinforcement is considered as a linear elastic material with no obvious yielding platform. Simulation specimens for beam bending are shown in Table 1 below.

| Specimen number | Concrete type         | Type of reinforcement | Longitudinal steel reinforcement |
|-----------------|-----------------------|-----------------------|---------------------------------|
| B-OC-OS         | Ordinary concrete     | General steel bars    | 2C14                            |
| B-HDC-OS        | High durability concrete | General steel bars     | 2C14                            |
| B-OC-GFRP       | Ordinary concrete     | GFRP steel bars       | 2C14                            |
| B-HDC-GFRP      | High durability concrete | GFRP steel bars       | 2C14                            |

The beam specimen size in this paper is 200mm×300mm×2100mm, the length of the longitudinal ribs is 2020mm, the thickness of the longitudinal rib protection layer is 35mm. Concrete material properties are defined as solid homogeneous and steel reinforcement is defined as trusses. The bottom surface of the lower pads at both ends of the beam is set as fixed supports with no displacement or cornering. The displacement-controlled loading method was used, and the loading speed was 0.1mm/s.

2.2 Load-Deflection Curve

For the bending analysis of the beam, the slope of the load-deflection curve represents the stiffness of the beam as a whole, and it can be seen from Figure 1 that the stiffness change trend of each specimen is similar, which can be divided into three stages. The first stage is the uncracked stage, and all four specimens, B-OC-OS, B-OC-GFRP, B-HDC-OS and B-HDC-GFRP, show a linear growth with no significant difference. As the load increases and reaches 20.16KN, the stiffness of the beam decreases significantly, the growth rate of the load slows down, and the maximum tensile stress of the longitudinal tensile steel of the beam is reached. The concrete in the stretched area begins to crack, with cracks appearing at the bottom, allowing a momentary drop in structural stiffness to fluctuate, which leads to the second stage—working with cracks. The load at this time is 71.66KN for B-OC-OS, 65.37KN for B-OC-GFRP, 71.574KN for B-HDC-OS, and 68.88KN for B-HDC-GFRP. As the loading progresses, the cracks in the concrete in the tensile zone increase, and the elastic retraction of the bottom longitudinal reinforcement results in the sharing of part of the compressive stress of the concrete at the top of the beam, thus appearing the phenomenon of "unloading", and the rate of stiffness change gradually becomes slower[3]. B-OC-OS and B-HDC-OS have faster load growth than B-OC-GFRP and B-HDC-GFRP because of stress redistribution due to concrete failure. In this paper, the modulus of elasticity of GFRP bar is $4.8 \times 10^4$MPa and that of ordinary steel bar is $2.0 \times 10^5$MPa, which is a big difference, and due to the small elongation of GFRP bar, the slope of the second stage of the curve of two different steel bars is different. In the third stage, the beam cracks reach complete, the reinforcement yields until the beam is destroyed, and as the deflection increases, the concrete is crushed and destroyed.
At this point the ultimate bearing capacity of four different curves can be obtained, the ultimate bearing capacity of B-OC-OS is 74.96KN, the ultimate bearing capacity of B-HDC-OS is 76.56KN, the ultimate bearing capacity of B-OC-GFRP is 85.66KN, the ultimate bearing capacity of B-HDC-GFRP has an ultimate load capacity of 80.89KN. As GFRP reinforcement is a linear material, it can bear part of the load after the reinforcement yields, so the ultimate bearing capacity is greater than ordinary reinforcement.

2.3 Positive Section Load Capacity

The bent members with different materials, concrete strength and reinforcement ratio are simulated with finite element analysis to obtain their bending performance and positive section bending capacity, and then according to the theoretical knowledge of positive section capacity of single-reinforced rectangular section bent members in *Principles of Concrete Structural Design* [4], the theoretical values are compared with the finite element simulation values, as shown in Table 2 below.

| Specimen number | Theoretical calculation (kN) | Calculated finite element value (kN) | Finite element value/theoretical value |
|-----------------|-----------------------------|-------------------------------------|--------------------------------------|
| B-OC-OS         | 86.2                        | 74.96                               | 0.86                                 |
| B-HDC-OS        | 87.8                        | 76.56                               | 0.87                                 |
| B-HDC-GFRP      | 81.1                        | 80.89                               | 0.99                                 |

From the table, it can be seen that the ratio between the FEM value and the theoretical value of each specimen has a certain regularity and large deviation, so the proposed correction formula for calculating the bending load bearing capacity of the positive section of GFRP reinforcement highly durable concrete is as follows.

\[
M \leq M_d = 0.91\alpha_f b h_0^2 \xi (1 - 0.5 \xi)
\]
3. Seismic Performance Analysis of Corrosion-resistant Reinforced Highly Durable Concrete Beams

3.1 Hysteresis Curve

Hysteresis curves are closely related to concrete material properties. In this paper, the plastic damage model proposed by Lubliner[5] and Lee[6] is used to define the plastic properties of concrete by parameters such as expansion angle and eccentricity, classify plastic damage into compression damage and tensile damage, and use two columns of damage parameters to simulate the degradation of elastic stiffness caused by damage. The damage parameters were calculated by \( d = 1 - \sqrt{\sigma / (E_0 \varepsilon)} \), as proposed by Sidoroff based on the energy equivalence principle[7]. Where \( d \) is the concrete damage factor, \( \sigma \) is the real concrete stress, \( \varepsilon \) is the concrete strain, and \( E_0 \) is the initial modulus of elasticity of concrete. Stiffness recovery coefficient is generally between 0.35 and 0.7, according to the data derived from the experiments of the subject group, where the stiffness recovery coefficient is 0.5. The hysteresis criterion is determined by the combination of the damage factor and the stiffness recovery coefficient, which simulates the unloading stiffness of concrete by discounting the tensile and compressive elastic stiffness of concrete. The hysteresis curve is the load-deformation curve of the structure under repeated loading, which reflects the deformation characteristics, stiffness degradation and energy consumption of the structure in the process of repeated loading, and is the basis for determining the resilience model and analyzing the nonlinear seismic response, reflecting the seismic performance of the structure [8]. The finite element results are output to obtain the hysteresis curves for each specimen as shown in Figure 2.

![Figure 2. Beam finite element hysteresis curve](image-url)
As we can see from the graph, the trend of change of the hysteresis curve of each specimen is more or less the same, the pinching effect is more obvious, and the whole is inverted S shape. Comparison of (a) and (b) shows that the hysteresis curves of the highly durable concrete are more full with rebar as an invariant. The reason is that basalt fibers and polypropylene fibers in highly durable concrete can effectively improve the ductility, impact resistance and toughness of concrete and improve the seismic performance of components. Comparing (b) and (d), with high durability concrete as the invariant, the hysteresis curves of ordinary steel reinforcement specimens are fuller than those of GFRP reinforcement specimens, indicating that the seismic performance of ordinary steel reinforcement is slightly better than that of GFRP reinforcement.

3.2 Skeletal Curve
The peak of the hysteresis loop in the hysteresis curve is connected to obtain the skeleton curve of the specimen, which can reflect the ductility, seismic energy dissipation, strength and stiffness degradation of the reinforced concrete node, and the specific output results are shown in Figure 3 below.

![Figure 3. Comparison of skeletal curves](image)

The graph shows that the four specimens skeleton curve change trend is basically the same, was elastic stage, elasto-plastic stage and the destruction of the three steps of the stage, the beginning of the loading, has not reached the yield load, displacement - load was linear elastic increase, the load gradually increased, the specimens into elasto-plastic until the limit load, the specimen load began to decrease, at this time the specimens began to destroy. The figure also clearly shows that the ultimate bearing capacity of N-HDC-OS is the largest, followed by N-HDC-GFRP, and N-OC-OS is the smallest.

3.3 Rigidity Degradation
Stiffness is the ability of a material or structure to resist elastic deformation when subjected to a force, and is a characterization of the ease with which a material or structure can be deformed elastically. The stiffness of a material is usually measured by its elastic modulus, E. In the macroelastic range, stiffness is a proportional coefficient of the part load proportional to displacement, i.e., the force required to cause a unit displacement. The change in stiffness is an important influencing factor and intuitive reflection of the change in the seismic performance of a specimen under horizontal reciprocating loads, so determining the change law of stiffness of a specimen under repeated loads is...
an important basis for studying its seismic performance[9]. According to the stiffness calculation formula proposed by Miao Jun.

\[ K_j = \frac{\sum_{i=1}^{n} P_j^i}{\sum_{i=1}^{n} u_j^i} \] (2)

Where: \( P_j^i \) is the load at the peak point of the i-th cycle for load displacement \( \Delta/\Delta y=j \); \( u_j^i \) is the deformation at the peak point of the i-th cycle for load displacement \( \Delta/\Delta y=j \); \( n \) is the number of cycles loaded. The stiffness degradation curve was obtained as shown in Figure 4 below.

![Figure 4. Comparison of stiffness degradation curves](image)

It can be seen from the figure that with the increase of loading displacement, the stiffness of the member decreases, and the overall stiffness degradation of the four specimens is basically the same, and the overall degradation of stiffness is slow, which has good seismic performance; The maximum initial stiffness of N-HDC-OS and the minimum initial stiffness of N-OC-GFRP is due to the low elongation of GFRP reinforcement, no obvious yielding section and small ductility, which leads to the reduction of ductility and stiffness of the member after the addition of the member, but the overall satisfaction to meet the seismic performance of the member, comparing the curves in the figure obviously shows that the high durability concrete has better stiffness and seismic ability to the member compared with ordinary concrete.

4. Analysis of the Seismic Performance of Highly Durable Concrete Frame Structures Made of Corrosion-Resistant Reinforcement

According to the South China Sea islands terrain and geomorphological environmental conditions and building seismic design code GB50011-2010 can be informed by the soil layer equivalent shear wave velocity and site cover layer thickness of the South China Sea reef area site category is divided into two categories, design seismic grouping for the first group, anti-seismic intensity of 8 degrees (0.2g). In order to simulate the performance advantages of high-durability concrete and GFRP tendons more clearly, we took an on-site architectural drawing in Hainan Province and simplified it into a three-storey, three-span reinforced concrete frame structure according to the concrete structural design code GB50010-2010. The beam cross-sectional dimensions are 400mm x 250mm, longitudinal tendons are 4C16. The stirrups are C8@100, The column cross-sectional dimensions are 400mm x 400mm, The whole is shown in Figure 5 below.
In this paper, the 8 degree (0.2g) seismic fortification is adopted, and the peak acceleration of the selected seismic recording is scaled up or down to make it equal to the peak acceleration of multi-occurrence earthquakes and rare earthquakes corresponding to the fortification intensity. Two natural waves (TAFT and EL Centro) and one artificial wave, which are representative of Class II soils at home and abroad, are selected to study the seismic performance of the whole frame structure system. In this paper, the artificial seismic wave is synthesized by the program Response Spectrum v2.0 and Simqke_gr. The principle is to describe the seismic vibration as a time function or response spectrum (Fourier or power spectrum). The reaction spectrum is calculated by plotting the maximum response (e.g. acceleration) of several single-degree-of-freedom vibration systems (spring-damped systems) with the same damping ratio and different self-oscillation frequencies on a self-oscillation frequency diagram. In this paper, the design parameters of the Chinese Building Seismic Design Code Response Spectrum v2.0 program are taken into account in order to simulate the seismic waves in accordance with the seismic conditions of the South China Sea islands and reefs by considering the site type, seismic protection level and design seismic groups to which the region belongs.

4.1 Displacement-Timing Curves
In this paper, abauqs software is used as the carrier to analyze and calculate the displacement-time curve of the displacement of each layer of a frame structure relative to the displacement of the bottom surface of the frame structure under a rare earthquake, as shown in Figure 6 below.
4.2 Inter-layer Displacement Angle
The basic requirements of the seismic design of the structure are: after determining the geometry of
the building space according to the function and building aesthetics requirements, according to the
level elevation of the structure, seismic environment and the use of the load, the adoption of economic
and reasonable structural system to make it have sufficient bearing capacity, stiffness and deformation
capacity, and under the estimated earthquake to achieve the expected performance objectives. The
most classical and commonly used seismic design method for building structures is based on the
design of the load capacity supplemented by the displacement angle calculation between the layers
[88]. The interlayer displacement is obtained by subtracting the displacement of each layer from the
corresponding layer height, and the interlayer displacement angle is obtained by comparing the
displacement of each layer with the corresponding layer height, and the data obtained are statistically
integrated (all maximum values below) in the following table 3.

![Figure 6. Comparison of displacement time course curves](image)
Table 3. Inter-layer displacement data for each specimen

| Specimen number | earthquake intensity | Substrate displacement angle | Mid-level displacement angle | Head displacement angle |
|-----------------|----------------------|------------------------------|-----------------------------|------------------------|
| B-OC-OS         | Multiple earthquakes | 1                            | 1                           | 1                      |
|                 |                      | 640                          | 812                         | 1045                   |
|                 | rare earthquake     | 1                            | 1                           | 1                      |
|                 |                      | 640                          | 812                         | 1045                   |
| B-HDC-OS        | Multiple earthquakes | 1                            | 1                           | 1                      |
|                 |                      | 611                          | 782                         | 915                    |
|                 | rare earthquake     | 1                            | 1                           | 1                      |
|                 |                      | 611                          | 782                         | 915                    |
| B-OC-GFRP       | Multiple earthquakes | 1                            | 1                           | 1                      |
|                 |                      | 666                          | 882                         | 1132                   |
|                 | rare earthquake     | 1                            | 1                           | 1                      |
|                 |                      | 666                          | 882                         | 1132                   |
| B-HDC-GFRP      | Multiple earthquakes | 1                            | 1                           | 1                      |
|                 |                      | 625                          | 745                         | 985                    |
|                 | rare earthquake     | 1                            | 1                           | 1                      |
|                 |                      | 625                          | 745                         | 985                    |

According to the seismic deformation check in the "Code for Seismic Design of Buildings", the maximum elastic inter-floor displacement of a frame structure under the action of rare earthquakes shall be in accordance with the following formula.

$$\Delta_{uc} \leq [\theta_e]h$$  \hspace{1cm} (3)

Which:  
- $\Delta_{uc}$ —— Maximum elastic intra-floor displacement under multiple earthquakes;
- $[\theta_e]$ —— Angle limit of elastic interlayer displacement, the structure of this paper is a reinforced concrete frame so $[\theta_e]$ is 1 \(^\circ\);  
- h——Calculation of floor heights, in this case 3000mm.

The inter-layer displacements of the specimens in Table 3 under rare earthquakes are validated on behalf of the test specimens, which can meet the limit values given in the specification and the requirements of seismic fortification.

5. Conclusion
Based on the actual engineering construction of South China Sea reefs and considering the high-temperature, high-humidity and high-salt-mist climate of South China Sea islands, this paper conducts a finite element modeling analysis of the seismic performance from beam and column members to nodes and frame structures based on the geographical conditions and the mechanical performance tests of high-durability concrete and GFRP reinforcement and the mechanical tests of high-durability concrete beam and column members of GFRP reinforcement by the research team.

(1) Through finite element modeling analysis of beams and columns of different steel and concrete types, it is concluded that, compared with ordinary reinforced concrete, the bearing capacity of GFRP reinforced high-durability concrete is lower but still satisfies the use requirements, and the formula for
correcting the positive section bearing capacity of GFRP reinforced high-durability concrete beams is obtained by comparing the theoretical calculation data;

(2) From the simulation analysis of the proposed static earthquake resistance of the beam, it is concluded that the hysteresis curve of each specimen is similar in fullness, generally shuttle-shaped, with pinching phenomenon in the middle; its skeleton curve reflects that the ultimate bearing capacity of GFRP reinforced high-durable concrete is larger than that of ordinary reinforced concrete; the stiffness degradation curve of each specimen shows a trend of fast and then slow overall, so the anti-seismic performance of GFRP reinforced high-durable concrete beam members is good.

(3) According to the extreme hot and humid climatic conditions, geological conditions and anti-seismic fortification requirements of the South China Sea reefs, a three-layer three-span frame structure with different reinforcement and concrete was constructed, and the anti-seismic performance analysis of the structure was carried out to obtain the displacement angle between each layer.

6. References
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