

Article

Bearing Behaviors of Grouted Sleeve Connections After High Temperature Followed by Water Cooling Under Cyclic Loading

Wangxi Zhang ^{1,2}, Jialu Wang ², Yibo Zhou ^{2,*}, Jia Wang ² and Weijian Yi ^{1,2}¹ Key Laboratory of Building Safety and Energy Efficiency of the Ministry of Education, Changsha 410082, China² College of Civil Engineering, Hunan University, Changsha 410082, China

* Correspondence: yzho9536@hnu.edu.cn

Abstract: As a common rebar connector in prefabricated projects, the grouted sleeve connection (GSC) affects structural performance during fire and seismic events. However, the combined impact of both factors may alter GSC performance, although most studies concentrate on high temperature or loading schemes. Few quantitative models are available for predicting the mechanical characteristics of post-fire GSCs under unidirectional tension, let alone cyclic loading. In this study, 18 GSC specimens were made and subjected to heating, water cooling, and cyclic loading. Thermal and mechanical loads caused rebar fracture below 400 °C, but pullout failure occurred beyond 400 °C. GSC performance declined as temperature and loading cycles increased. Based on this test and several previous investigations, predictive models with guaranteed rates for GSC performance after high temperature by water cooling under uniaxial and cyclic loading were constructed. According to the predictive models, the four parameters (including yield strength, ultimate strength, elastic modulus, and ultimate strain) of the GSCs using HRB400 rebars can be obtained.

Keywords: grouted sleeve connection (GSC); cyclic loading; high temperature; water cooling; mechanical performance; predictive model



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1. Introduction

Due to global construction industrialization, prefabricated concrete (PC) constructions are extensively utilized. However, structural integrity remains a concern [1], especially when faulty connections degrade the integrity. As one of the most crucial and dependable methods for connecting rebars in prefabricated structures, GSC directly influences structural integrity and reliability, necessitating that connections do not fail prior to the overall structures. Given the unavoidability and severity of fire and earthquake damage to structures in real-world engineering settings, it is crucial to understand GSC mechanical features during fire and seismic disasters.

A fire is one of the most critical risks that may occur in constructed structures during their service life. High temperatures induce varying degrees of deterioration in grout materials and rebars, with increased temperature correlating to heightened deterioration severity [2,3]. The microstructure of grouting material varies from compact to loose as temperature rises [4], and widespread cracks are noticeable [5]. Finite element modeling reveals that the grout is severely damaged, resulting in a ring-shaped damage zone within the sleeve [6]. With the increase in temperature history, both the ultimate bearing capacity and ductility of the GSCs decrease [7–10]. When the temperature reaches a certain threshold (normally between 600 °C and 800 °C [5]), the failure mode changes from rebar fracture

to rebar pullout. Rebar pullout means the GSCs experience bond failures, considerably impacting the structural integrity [11]. The different cooling methods also have an impact. Under the same high-temperature settings, water cooling decreases the mechanical performance of GSCs more than natural cooling [3]. The water cooling procedure produces a temperature gradient effect, intensifying interior damage to the specimens [12]. A comparison test found that specimens treated to 600 °C would have bonding failure under single tensile testing following water cooling, whereas specimens cooled naturally would suffer rebar damage [3].

Seismic damage to prefabricated structures is often fatal in practical construction environments. Therefore, the performance of post-fire GSCs should be investigated under cyclic loading. Uniaxial tensile behavior has been extensively researched [13–15]. However, cyclic loading further damages the mechanical properties of GSCs [16,17]. In comparison to uniaxial tension, cyclic loading causes GSC stiffness deterioration to be more noticeable [18,19]. The residual deformation of GSCs increases with the number of cyclic loadings [20]. The configurations of the load versus displacement curves appear to be largely uniform; yet, the increased temperature markedly influences the peak loads of post-fire specimens [8]. Significant grout damage is observed near the sleeve's extremity, with portions of the grout material detaching and creating conical depressions [21]. In seismic zones, particularly for buildings that have endured fires, the post-fire seismic performance of connections must be thoroughly evaluated to inform post-disaster assessment and restoration efforts.

Many researchers have made valuable contributions to the summarization and forecasting of the performance of GSCs. Multiple predictive models were developed for room temperature. The maximum tensile load of the GSCs under uniaxial tensile stress can be approximated using a predictive equation [14]. A formula was developed to predict the length of the inelastic area and the tensile strength of GSCs under uniaxial tensile loading [22]. A load-slip constitutive model for GSCs under uniaxial tension with different deficient situations was proposed [23]. On the basis of 334 datasets, an extremely applicable formula for calculating the ultimate bond strength of GSCs was suggested [24]. A theoretical diagnostic model and a risk assessment catalog may serve as a potential advancement toward the development of a computerized diagnostic model for the damaged connection [25]. For high temperatures, several predictive models were also developed. In order to determine the yield and ultimate loads of the heat-damaged GSCs following various loading regimes, a bilinear model was developed [26]. Under various grouting deficiencies following a fire, theoretical models were developed to represent the bond stress-slip constitutive relationship between rebar and grout sleeves in GSCs [11]. Through statistical regression, the formula for bond stresses at raised and post-elevated temperatures was determined [5]. A value of 0.178 was utilized to denote the cumulative damage in post-fire GSCs due to cyclic loadings, which established the theoretical framework for calculating bearing capacity [8]. The concrete cover enclosing the GSC is taken into account as an influencing factor in the prediction formula of bonding strength and peak temperatures [27].

Currently, there are not many models that can predict how post-fire GSCs will behave in terms of strength, deformation, and other factors that are related, particularly in the context of cyclic loading. Moreover, the impact of water cooling is not taken into account in conditions of simultaneous elevated temperature and cyclic loading. Water cooling is considered appropriate to better align test results with real-world situations, given its common use in quelling fires. Also, the GSC's high-temperature performance varies, making it hard to use the mathematical formula derived from test data that was made to measure this performance reliably in real-life engineering situations. It is essential to aggregate additional data extensively and prioritize probabilistic dependability to achieve a specified guarantee rate for the high-temperature performance prediction model of the

connection. Consequently, there exists an immediate necessity to conduct research on the bearing behaviors and to formulate a predictive model for GSCs after high temperature by water cooling.

In this study, GSCs with 14 mm diameter rebars were subjected to high temperature, water cooling, and cyclic loading to find out their bearing behaviors. The major variable in this investigation was temperature. The reliability of GSCs was validated using test criteria including failure mechanisms, yield strength, ultimate strength, and ductility. On the other hand, predictive models with a certain guaranteed rate for the performance of GSCs subsequent to high temperature by water cooling under uniaxial loading and cyclic loading were developed. The subsequent results provided a theoretical reference to assist in the evaluation and reinforcement of GSCs post-fire and post-earthquake with water cooling, hence broadening the performance evaluation within the specifications under intricate practical engineering settings. Consequently, the risk assessment of the overall structure and the strategic planning of maintenance actions could be enhanced by this.

2. Materials and Methods

2.1. Materials

According to GB/T 228.1-2021 [28] and ISO 6892-1:2009 [29], three rebars were put aside during GSC specimen preparation for ambient temperature material performance testing. Table 1 lists this batch's rebar qualities.

Table 1. Measured properties of rebar.

Material	Diameter (mm)	Yield Strength (N/mm ²)	Ultimate Strength (N/mm ²)
HRB400 [30]	14	474.2	612.0

The grouting material was chosen according to JG/T 408-2019 [31]. Eighteen test blocks of grouting material measuring 40 mm × 40 mm × 160 mm were reserved, and a performance test after heating to different temperatures followed by water cooling (including ambient temperature AT, 200 °C, 400 °C, 600 °C, 800 °C, and 1000 °C) was conducted in accordance with GB/T 17671-2021 [32] and ISO 679:2009 [33]. Table 2 shows the material properties of this batch of grouting material.

Table 2. Measured properties of grouting material.

Material	Compression Strength After Different Temperatures (N/mm ² /°C)
Cementitious grout	93.1/AT; 83.2/200; 78.3/400; 55.5/600; 39.5/800; 14.6/1000

The grout sleeves utilized in this study are fully grouted sleeves, which comply with JGT 398-2019 [34]. The specific configuration and parameters are shown in Figure 1 and Table 3.

Table 3. Parameters of the fully-grouted sleeve.

Material	Outer Diameter (mm)	Inner Diameter (mm)	D_i (mm)	D_o (mm)	Tensile Strength (N/mm ²)
Carbon structural steel	46	34	30	26	610

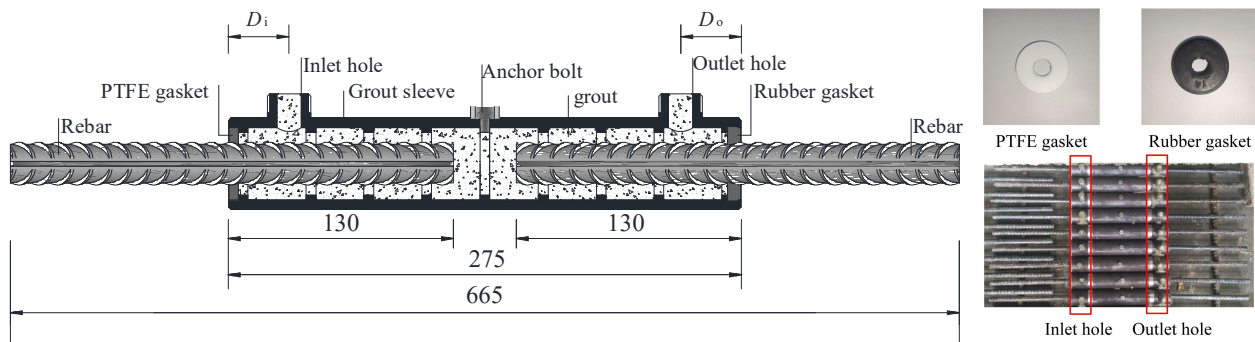


Figure 1. Sketches of the specimen (mm).

2.2. Design and Fabrication of Specimens

The temperature is the only changing contributing factor considered in this experiment, and the temperatures used were AT, 200 °C, 400 °C, 600 °C, 800 °C, and 1000 °C. For deviation control, three parallel specimens were employed per temperature. The specimen identification number is “CL-AT/200/400/600/800/1000-1/2/3,” where “CL” stands for repeated tension and compression loading (cyclic loading), “AT/200/400/600/800/1000” for the treatment temperature, and “1/2/3” for the specimen number under identical conditions. Figure 1 shows these specimens’ geometric dimensions and structure according to JGJ 355-2015 [35]. The grout sleeve has a rubber gasket at one end to center the rebar. To align the other end, a special polytetrafluoroethylene (PTFE) gasket is used. The specimens were subsequently subjected to standard curing conditions for 28 days after grouting.

2.3. Heating and Cooling Program

The specimens were heated in a tubular heating furnace, as shown in Figure 2b,c. The specific heating–cooling procedure is illustrated in Figure 2a.

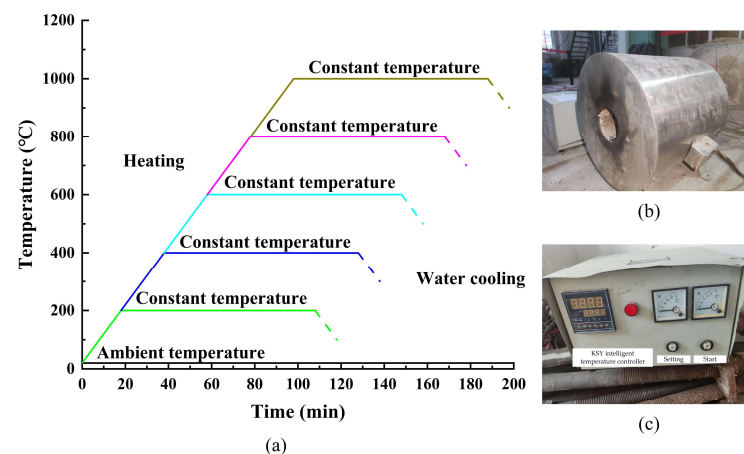


Figure 2. Heating procedure and device; (a) Heating procedure; (b) Furnace; (c) Intelligent temperature control box.

2.4. Test Setup and Loading Scheme

The loading facility is the repeated tension–compression testing equipment for rebars at Hunan University, as shown in Figure 3. Considering the recommended loading rate [36], previous research on the impact of different loading rates on GSCs [37], and the specific conditions of the loading facility, a displacement loading mode with a speed of 5 mm/s was chosen.

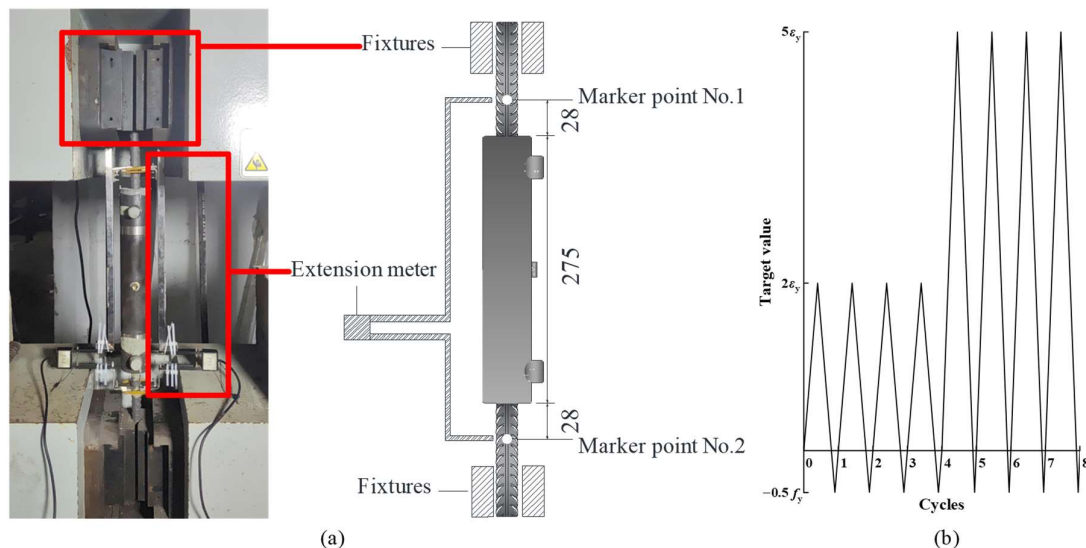


Figure 3. Test setup and loading scheme; (a) Loading device; (b) CL cyclic loading scheme.

In accordance with JGJ 355-2015 [35], the loading scheme is shown in Equation (1), where ε_{sy} represents the rebar strain when it reaches the standard value of yield strength. In accordance with JGJ 107-2016 [36], the ε_{sy} adopted in this study is 0.002; f_{sy} represents the standard yield strength value of rebars; L_g represents the calculated length of GSC under cyclic loading, as shown in Equation (2); l_{GSC} and d represent the sleeve length and diameter of connected rebars, respectively.

$$0 \rightarrow (2\varepsilon_{sy}L_g \rightarrow -0.5f_{sy}) \text{ repeat 4 times} \rightarrow (2\varepsilon_{sy}L_g \rightarrow -0.5f_{sy}) \text{ repeat 4 times} \rightarrow \text{Failure} \quad (1)$$

$$L_g = L_{GSC}/4 + 4d \quad (2)$$

2.5. Data Measurement

In accordance with JGJ 355-2015 [35], the specimen's displacement measuring point was chosen as twice the rebar's diameter from both sides of the sleeve (Figure 3). During loading, the force sensor and pull line displacement sensor independently sensed and recorded the specimen load and relative displacement fluctuations between two fixtures. Due to the fact that the relative displacement surpassed the intended measurement length, an additional measurement technique was required. The image recognition technology has a broad range but comparatively low measurement accuracy, in contrast to the extension meter's limited range and high accuracy. Therefore, the displacement of GSCs was determined by combining the two techniques. The term "force" in the subsequent figures denotes the load that the loading device applies to both ends of the GSC specimen through the fixtures, while "displacement" denotes the relative displacement between the two marker points on the specimen, as illustrated in Figure 3.

3. Results

3.1. Appearance of GSCs After High Temperature and Water Cooling

The furnace was enclosed, so specimens could not be observed during heating. Occasional cracking sounds from the furnace revealed that the GSC grouting material cracked arbitrarily at high temperatures. After heating, the specimen was removed from the furnace. On the surface of the specimen, no substantial reddening was observed when the set temperature was below 600 °C; nevertheless, discernible red burn marks appeared when

the temperature surpassed 600 °C. Upon water cooling, a substantial amount of water vapor emerged. The higher the set temperature, the more water vapor was generated.

Comparative analyses of the sleeves and grouting material's surface properties after thermal treatment revealed observable changes, as depicted in Figure 4. A gradual increase in temperature changed the sleeve's look from brilliant to dark, from silver-black to rust-like reddish brown to blue-gray. Peeling was observed to commence at 800 °C and was subsequently intensified at 1000 °C. As the temperature increased, the color of the grouting material near the end of the sleeve gradually lightened and turned yellow; however, no significant cracking was detected. The surface behavior of the sleeve after high temperature was similar to the observations of Hu et al. [10] and Chen et al. [11].



Figure 4. Surface condition of sleeves after heating and water cooling.

3.2. Cyclic Loading Results

Samples undergo cyclic loading after thermal treatment. Rebar fracture and pullout are the main failure modes. All specimen testing was thoroughly documented, and Figure 5's curves were obtained by data analysis. Table 4 shows curve-extracted GSC parameters. The shapes of force-displacement curves are highly identical to the results from previous studies about post-fire GSCs [38,39]. As Liu et al. [26] have concluded, these curves can be divided into four components: the ascending segment, yielding platform, strengthening segment, and descending segment. The fourth portion of the curves did not exhibit a sudden decline in GSCs with rebar pullout failure; rather, it exhibited a slow and fluctuating trend.

Table 4. Key parameters of GSCs' performance.

Specimen No.	Yield Load, F_y (kN)	Yield Displacement, Δ_u (mm)	Ultimate Load, F_u (kN)	Ultimate Displacement, Δ_u (mm)	Failure Modes
CL-AT-1	68.53	0.55	93.30	13.30	I
CL-AT-2	78.02	0.74	98.71	13.55	I
CL-AT-3	65.29	0.45	89.37	14.05	I
CL-200-1	65.86	0.52	89.79	18.87	I
CL-200-2	67.94	0.52	91.66	19.21	I
CL-200-3	70.31	0.59	92.93	18.37	I
CL-400-1	65.75	0.86	90.41	25.40	I
CL-400-2	65.52	1.32	88.22	22.46	II
CL-400-3	65.91	1.16	88.98	24.56	II
CL-600-1	67.66	1.88	85.17	14.93	II
CL-600-2	62.44	1.11	78.37	14.15	II
CL-600-3	64.87	1.08	76.56	10.42	II
CL-800-1	47.86	0.99	63.78	4.31	II

Table 4. Cont.

Specimen No.	Yield Load, F_y (kN)	Yield Displacement, Δ_u (mm)	Ultimate Load, F_u (kN)	Ultimate Displacement, Δ_u (mm)	Failure Modes
CL-800-2	46.06	0.86	63.28	4.82	II
CL-800-3	51.26	1.54	68.43	5.11	II
CL-1000-1	43.57	1.19	47.04	2.09	II
CL-1000-2	33.28	1.57	35.33	1.97	II
CL-1000-3	47.74	2.43	51.34	3.24	II

Yield load and yield displacement are the endpoints of the elastic straight-line segment of the load-displacement curves, and ultimate load and ultimate displacement are the maximum load and its corresponding displacement. For the failure modes, “I” represents rebar fracture and “II” represents rebar pullout.

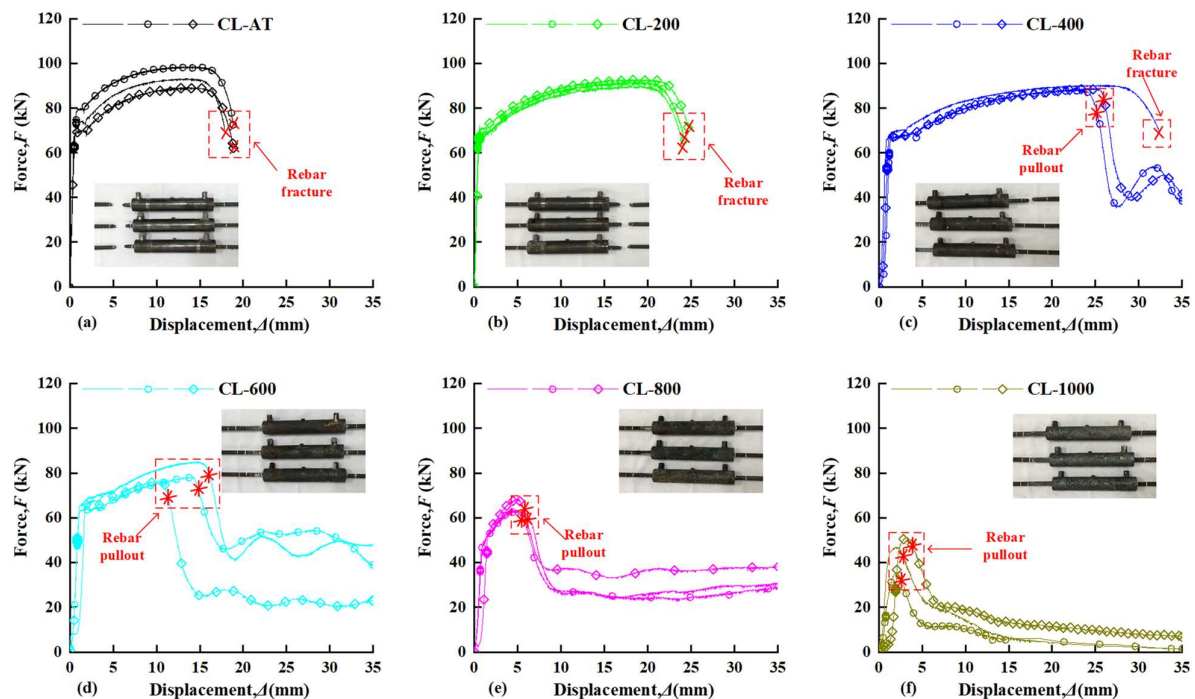


Figure 5. Cyclic loading results of GSCs; (a) CL-AT; (b) CL-200; (c) CL-400; (d) CL-600; (e) CL-800; (f) CL-1000.

3.3. Failure Modes

When the rebars were pulled off, the fracture points randomly occurred outside the sleeve. PC constructions depend on grout sleeves to connect rebars. Therefore, fractures of rebar are generally acceptable. Unreliable connections are indicated by rebar pullout. With the increase in temperature, the transition from rebar fracture to pullout gradually occurred, indicating that elevated temperatures can diminish the bonding performance between rebars and the grouting material, rendering the connection less reliable. An alignment of the failure modes of GSCs with those of cast-in-situ connections should be incorporated into the structural design of PC structures in order to guarantee the safety of these structures. In order to ensure that prefabricated structures are safe, it is essential to conduct an accurate analysis of the GSC failure mode in order to enhance the design of the structure.

Two different types of failure were found in the connections at 400 °C. This means that 400 °C is the critical temperature at which GSCs go from being reliable to not being reliable under cyclic loading following heating and water cooling. The conclusion that the failure mode changes with high temperature is consistent with the previous research results, but the critical temperature of the failure mode decreases [3,5,40]. On the one hand, void spaces and microscopic fissures form in grouting materials when bound and free water evaporates

inside them due to elevated temperatures. According to tests on grouting materials, their compressive strengths drop a lot when they are exposed to high temperatures and then cooled down with water (see Table 2). Cyclic loading, on the other hand, does more damage to the grouting material inside the GSCs and the contact interface between the grouting material and the rebars than unidirectional tension. The grout at the front end of the steel rib is compressed and fractured when the connection is stretched; the grout at the back end of the steel rib is also crushed when the connection is compressed. Under the action of reciprocating tension and compression, the damage range of grouting material around the steel rib gradually expands and progressively accumulates under the repeated load. As the damage extends, a cylindrical shear surface forms at the height of the rib. At this point, the mechanical bite force is essentially lost, and only the friction force is involved. The steel bar is progressively pulled out.

3.4. Strength, Strain, and Elastic Modulus

Figure 6a shows specimen yield and ultimate strength. The yield strength demonstrated minor fluctuation at lower temperatures. It displayed a drop when the temperature went above 600 °C. Similarly, the ultimate strength exhibited negligible sensitivity to temperature fluctuations at lower temperatures; however, it progressively decreased once the temperature surpassed 400 °C. The strength of the connection at lower temperatures depends mostly on the rebar. Conversely, elevated temperatures result in modified failure modes that render the bond strength between rebars and grouting material the determining factor. Unfortunately, this bond strength typically does not totally recover from heating and cooling, which has a propensity to decrease as the temperature rises. Connection strength varies with temperature due to mechanisms of failure. Ultimate strength decreases more than yield strength at high temperatures. In comparison to the naturally cooled specimens, the final strength of the water-cooled specimens exhibited a more pronounced drop following exposure to high temperatures, which aligned with the occurrence of pull-out failure [5].

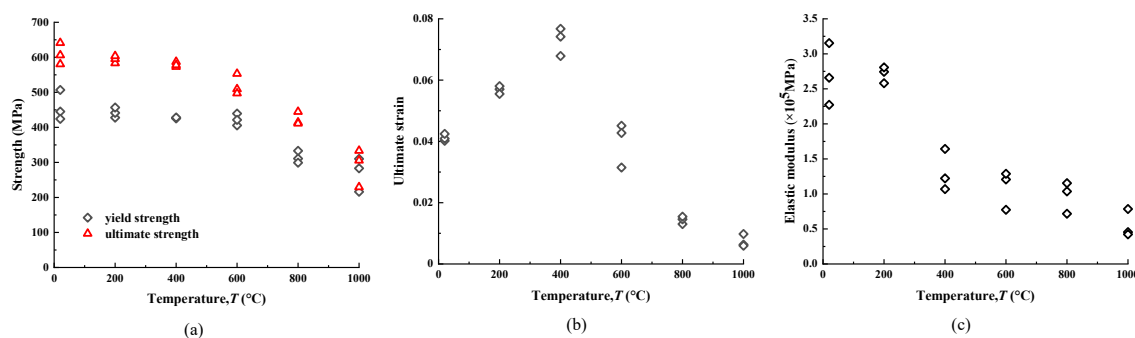


Figure 6. The strength, strain, and elastic modulus of the GSCs; (a) The yield strength and ultimate strength; (b) The ultimate strain; (c) The elastic modulus.

Figure 6b shows the highlighted segment's ultimate strain (Figure 3). Ultimate strain increased proportionally when the temperature was limited to 400 °C or lower. Nevertheless, as the temperature rose above 400 °C, the ultimate strain exhibited a progressive diminishing rate of decrease. As temperature rose, the elastic modulus of GSCs fell due to the loss of bonding strength between the rebar and grouting material, as shown in Figure 6c.

3.5. Hysteresis Curve

To clearly demonstrate the load-displacement curve under cyclic loading, a representative specimen was selected from each temperature group among the three parallel specimens, as depicted in Figure 7.

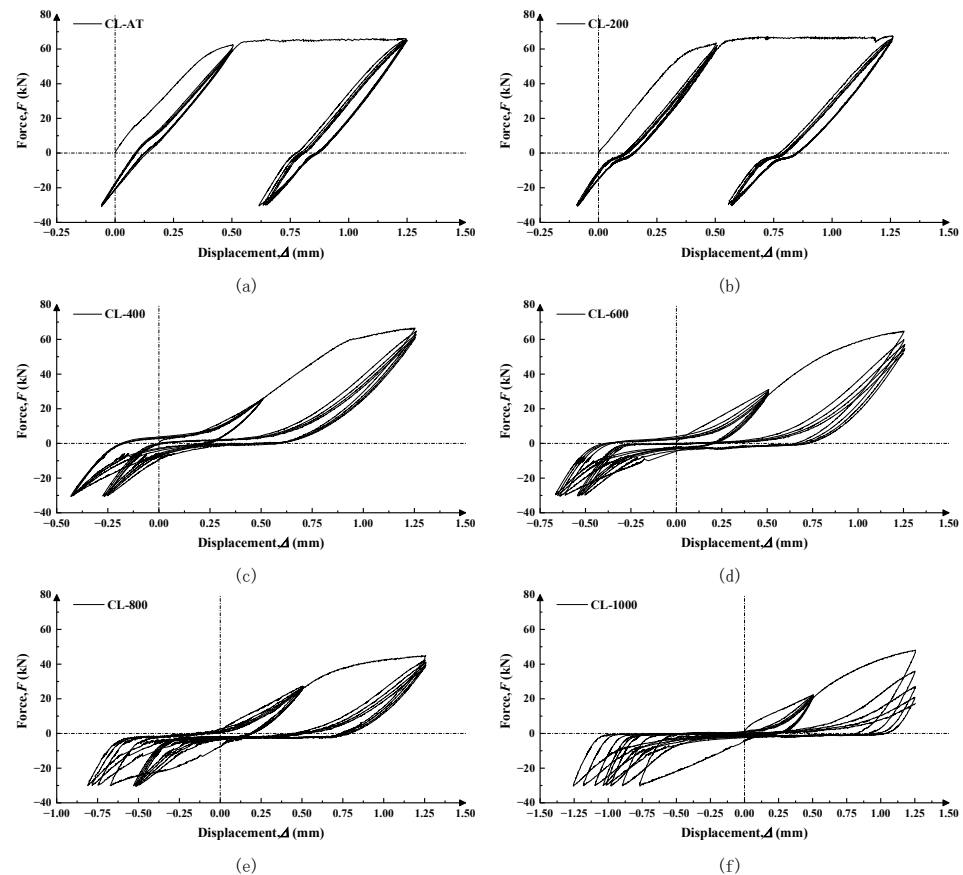


Figure 7. Load-displacement hysteresis curves of the GSCs; (a) AT; (b) 200 °C; (c) 400 °C; (d) 600 °C; (e) 800 °C; (f) 1000 °C.

The tensile and compressive cycles are repeated four times in each stage. As the number of cycles increases, the grouting material between the rebar and grouting material gradually wears down, reducing bonding efficacy. The reduced connection strength needed to achieve a comparable displacement shows the deterioration. Additionally, the platform section within the hysteresis loop becomes longer with a more pronounced pinching phenomenon. The feature of a pinching effect is similar to that observed by Liu et al. [8]. The pinching results in a smaller area and weaker energy dissipation capacity. However, these phenomena are primarily concentrated during the first cycle. The degradation caused by cyclic loading worsens with temperature, just like the finding by Wang et al. [41]. At 1000 °C, the cyclic stage has a higher maximum load than the uniaxial stage. In contrast to the first stage, the performance degradation observed during the second stage is more conspicuous. The platform region of the hysteresis curve lengthens, pinching more. The grouting material's enhanced fracture severity causes larger residual deformation after the second cycle than the first. As a result, the degradation of bond performance becomes progressively more evident as the treatment temperature increases.

3.6. Evaluation of Connection Performance

JGJ355-2015 [35], Ling et al. [42], and ACI318-19 [43] proposed several indicators for evaluating the performance of GSCs, as shown in Table 5.

Table 5. Evaluation indicators of GSCs' performance.

Evaluation Indicators	Computational Formula	Criteria
Yield strength ratio	$R_y = F_y / F_{sy}$	$R_y \geq 1.0$
Strength ratio	$R_s = F_u / F_{sy}$	$R_s \geq 1.25$
Ultimate strength ratio	$R_u = F_u / F_{su}$	Rebar fracture $R_u \geq 1.0$ Rebar pullout $R_u \geq 1.15$
Ductility ratio	$R_d = \Delta_u / \Delta_y$	$R_d \geq 4 \sim 6$

F_y , F_u , Δ_y , and Δ_u represent the yield load, ultimate load, yield displacement, and ultimate displacement of the GSC, correspondingly. F_{sy} and F_{su} represent the loads calculated according to the standard values of yield strength and ultimate strength of the rebars, respectively.

In the above table, R_y , R_s , and R_u are strength performance indicators, while R_d is the deformation performance indicator. The evaluation results of connections are presented in Table 6.

Table 6. Evaluation of GSCs' performance.

Specimen No.	R_y	R_s	R_u	R_d	Failure Mode	Acceptability
CL-AT-1	1.11	1.52	1.12	24.00	I	Acceptable
CL-AT-2	1.27	1.60	1.19	18.35	I	Acceptable
CL-AT-3	1.06	1.45	1.08	31.57	I	Acceptable
CL-200-1	1.07	1.46	1.08	36.55	I	Acceptable
CL-200-2	1.10	1.49	1.10	36.90	I	Acceptable
CL-200-3	1.14	1.51	1.12	31.36	I	Acceptable
CL-400-1	1.07	1.47	1.09	29.51	I	Acceptable
CL-400-2	1.06	1.43	1.06	17.04	II	Unacceptable
CL-400-3	1.07	1.45	1.07	21.19	II	Unacceptable
CL-600-1	1.10	1.38	1.02	7.94	II	Unacceptable
CL-600-2	1.01	1.27	0.94	12.71	II	Unacceptable
CL-600-3	1.05	1.24	0.92	9.62	II	Unacceptable
CL-800-1	0.78	1.04	0.77	4.34	II	Unacceptable
CL-800-2	0.75	1.03	0.76	5.62	II	Unacceptable
CL-800-3	0.83	1.11	0.82	3.33	II	Unacceptable
CL-1000-1	0.71	0.76	0.57	1.75	II	Unacceptable
CL-1000-2	0.54	0.57	0.42	1.25	II	Unacceptable
CL-1000-3	0.78	0.83	0.62	1.33	II	Unacceptable

The background color means the indicators that fail to meet the criteria in Table 5 and thus the GSC's performance become unacceptable.

With increasing temperature, the three strength performance indicators are initially minimally affected by temperature and subsequently decrease. This change trend is similar to that of the yield load and ultimate load. Regarding the connection with the failure mode of rebar fracture, all strength performance indicators meet the requirements. For connections with rebar pullout failure, R_s and R_y meet the requirements at low temperatures; however, they fail to meet them at higher temperatures. Moreover, R_u is more challenging to be satisfied with than R_s and R_y under high-temperature conditions. None of the pullout-failed connections meet R_u criteria. The deformation performance indicator at 200 °C is greater than that at ambient temperature but decreases as the temperature increases afterwards. R_d exceeds 6 when the temperature does not exceed 600 °C, meeting the requirements; however, R_d at 1000 °C is below 4, failing to meet the requirements. The investigation shows that cyclic loading after heating and water cooling makes it harder for connections to meet performance standards, especially those with pullout failure.

4. A Predictive Model for the GSCs' Performance After Heating and Water Cooling

4.1. Data Collection

Based on the experimental data above and previous studies conducted by the research group [3,40,44,45], a predictive model for the strength and deformation characteristics of GSCs subjected to uniaxial loading or cyclic loading subsequent to heating and water cooling was developed using a probability-based statistical approach. The predicted model makes GSC performance test results easy to apply in real engineering, guiding fire-resistant design and post-fire safety assessment of prefabricated reinforced concrete structures.

GSCs operate similarly to rebars after high temperatures; hence, their stress–strain curve is mostly dictated by their yield point and ultimate point. The stress–strain curve of connections after high-temperature exposure is simplified to a bifurcation model using the curve of rebars exposed to high temperatures to facilitate engineering applications. Models are determined by yield strength, ultimate strength, ultimate strain, and elastic modulus.

To facilitate the investigation of the influence of high temperature on connection performance, four influence coefficients are put forward, including $f_{y,T}/f_{y,AT}$, $f_{u,T}/f_{u,AT}$, E_T/E_{AT} , and $\varepsilon_{u,T}/\varepsilon_{u,AT}$ ($f_{y,T}/f_{y,AT}$ denotes the connection's yield strength after temperature T versus that at ambient temperature. Likewise, $f_{u,T}/f_{u,AT}$, E_T/E_{AT} and $\varepsilon_{u,T}/\varepsilon_{u,AT}$ denote ultimate strength, elastic modulus, and ultimate strain, employing the identical computational approach). These coefficients are illustrated in Figure 8.

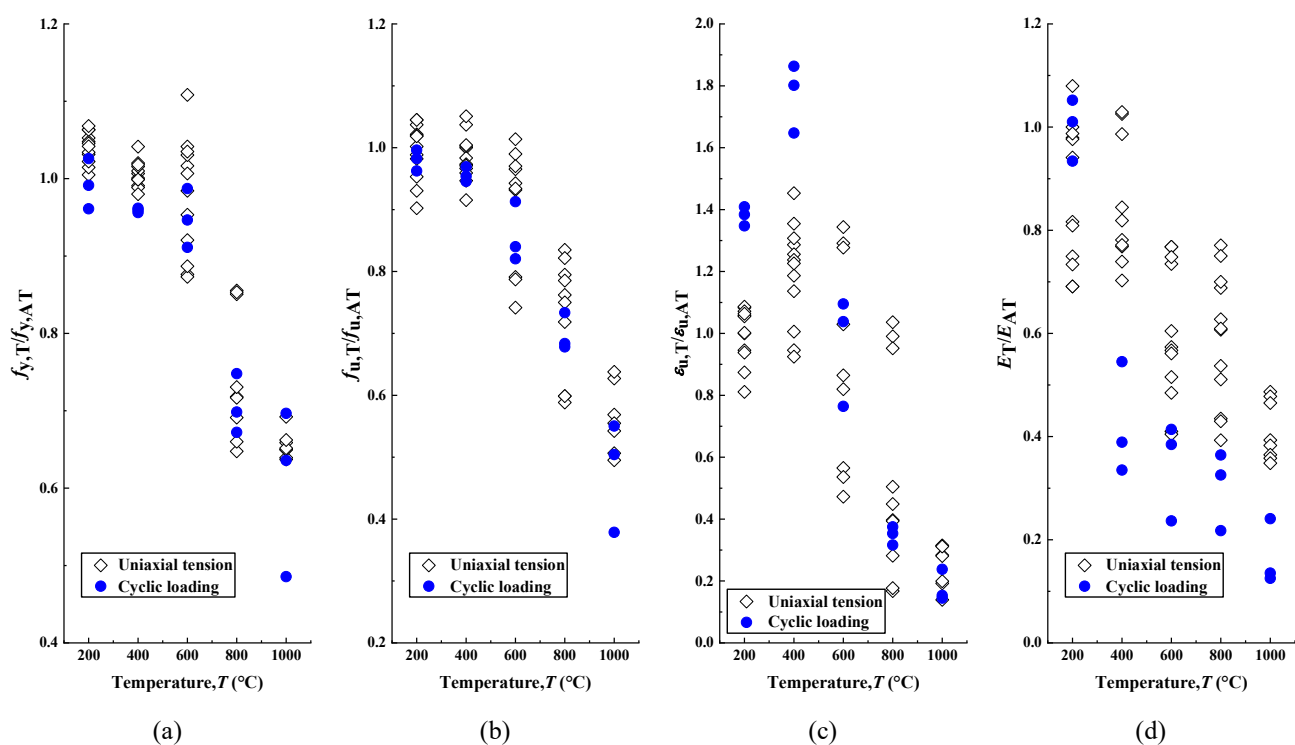


Figure 8. Temperature influence coefficients for connections after heating, water cooling, and different loading schemes; (a) Yield strength; (b) Ultimate strength; (c) Ultimate strain; (d) Elastic modulus.

4.2. Normal Analysis

Numerous factors affect grouting material and rebar application discreteness. To ensure the reliability of reinforced concrete structures, it is necessary to have a certain guaranteed rate for the performance of materials used in structural design. According to GB 50068-2018 [46], the standard value for the strength of steel and concrete at ambient temperature has a guaranteed rate of 95%. Similarly, T/CECS 252-2019 [47] indicates that

the temperature influence coefficient on the strength of rebar and concrete after exposure to high temperatures also has a guaranteed rate of 95%. Referring to these specifications, when simplifying GSCs as a whole for structural analysis, it is crucial to ensure that their strength at high temperatures remains guaranteed at a rate of 95%. If the actual strength of such connections at ambient temperature is known, establishing a quantitative model with a guaranteed rate of 95% for their temperature influence coefficient on strength becomes essential. Furthermore, according to GB 50068-2018 [46], a guaranteed rate requirement is set at 50% for standard values regarding rebars' elastic modulus at ambient temperature. Therefore, it becomes imperative to establish a quantitative model with a guaranteed rate set at 50% for both elastic modulus and ultimate strain's temperature influence coefficients on connection performance under high temperatures.

The temperature influence coefficients of each connection performance are classified to see if they are well fitted on a normal distribution. Due to the limited sample size (less than 50), the Shapiro–Wilk test [48] was adopted. The results are presented in Table 7. It can be observed that all of the data exhibit normal distribution characteristics, as indicated by p -values greater than 0.05 [48,49]. Given that the strength of grouting materials involved in the data collected is between 85 and 95 MPa, this paper does not address the impact of grouting materials with strengths beyond this specified range.

Table 7. p -value of temperature influence coefficients of connections after heating, water cooling and loading.

Loading Scheme	Strength of Grouting Material (MPa)	Influence Coefficient	Temperature $T/^{\circ}\text{C}$				
			200	400	600	800	1000
Uniaxial loading	85–95	$f_{y,T}/f_{y,AT}$	0.78	0.91	0.42	0.06	0.12
		$f_{u,T}/f_{u,AT}$	0.18	0.97	0.05	0.07	0.26
		E_T/E_{AT}	0.15	0.07	0.18	0.57	0.09
		$\varepsilon_{u,T}/\varepsilon_{u,AT}$	0.07	0.54	0.23	0.06	0.08
Cyclic loading		$f_{y,T}/f_{y,AT}$	0.93	0.81	0.93	0.67	0.54
		$f_{u,T}/f_{u,AT}$	0.79	0.67	0.39	0.17	0.50
		E_T/E_{AT}	0.68	0.48	0.30	0.49	0.15
		$\varepsilon_{u,T}/\varepsilon_{u,AT}$	0.79	0.54	0.31	0.70	0.16

4.3. Predictive Model

By comparing the high-temperature performance of GSCs and rebars and consulting the high-temperature performance calculation model for the rebars that are listed in Table 8, the formula for calculating the performance of connections after heating and water cooling was determined. As this study solely focused on grout sleeve splicing of HRB400 rebars, only the high-temperature constitutive model of HRB400 rebars was selected for comparative analysis.

Figure 9 shows the typical predictive model for uniaxial rebar performance after heating and water cooling. The temperature influence coefficients of the connection under uniaxial loading and cyclic loading with a certain guaranteed rate are depicted in Figure 9.

Table 8. Calculation model of rebar performance after high temperature.

Source	Computational Model				Scope of Application
[50] (I)	$f_{y,SR,T}/f_{y,SR,AT} = \begin{cases} 1 \\ 1 - 5.82 \times 10^{-4}(T - 500) \end{cases}$				$\begin{pmatrix} 20\text{ }^{\circ}\text{C} \leq T \leq 500\text{ }^{\circ}\text{C} \\ 500\text{ }^{\circ}\text{C} < T \leq 1000\text{ }^{\circ}\text{C} \end{pmatrix}$
	$f_{u,SR,T}/f_{u,SR,AT} = \begin{cases} 1 \\ 1 - 4.85 \times 10^{-4}(T - 500) \end{cases}$				$\begin{pmatrix} 20\text{ }^{\circ}\text{C} \leq T \leq 500\text{ }^{\circ}\text{C} \\ 500\text{ }^{\circ}\text{C} < T \leq 1000\text{ }^{\circ}\text{C} \end{pmatrix}$
	$E_{SR,T}/E_{SR,AT} = \begin{cases} 1 \\ 1 - 1.30 \times 10^{-4}(T - 500) \end{cases}$				$\begin{pmatrix} 20\text{ }^{\circ}\text{C} \leq T \leq 350\text{ }^{\circ}\text{C} \\ 350\text{ }^{\circ}\text{C} < T \leq 1000\text{ }^{\circ}\text{C} \end{pmatrix}$
[51] (II)	$\varepsilon_{u,SR,T} = [100 - 0.15(f_y - 300)] \varepsilon_y$				$20\text{ }^{\circ}\text{C} \leq T \leq 1000\text{ }^{\circ}\text{C}$
	$f_{y,SR,T}/f_{y,SR,AT} = \begin{cases} 1 \\ 1 + 2.33 \times 10^{-4}(T - 20) - 5.88 \times 10^{-7}(T - 20)^2 \end{cases}$				$\begin{pmatrix} 20\text{ }^{\circ}\text{C} \leq T \leq 400\text{ }^{\circ}\text{C} \\ 400\text{ }^{\circ}\text{C} < T \leq 800\text{ }^{\circ}\text{C} \end{pmatrix}$
	$E_{SR,T}/E_{SR,AT} = 1$				$20\text{ }^{\circ}\text{C} \leq T \leq 800\text{ }^{\circ}\text{C}$
[52] (III)	$f_{y,SR,T}/f_{y,SR,AT}$ (Mean value)	$f_{y,SR,T}/f_{y,SR,AT}$ (95% guaranteed rate)	$f_{u,SR,T}/f_{u,SR,AT}$ (Mean value)	$f_{u,SR,T}/f_{u,SR,AT}$ (95% guaranteed rate)	
	1.00	0.94	1.00	0.95	200 °C
	1.02	0.89	0.99	0.91	400 °C
	0.99	0.90	0.97	0.92	600 °C
	0.85	0.76	0.90	0.72	800 °C
	0.86	0.83	0.84	0.59	1000 °C

$f_{y,SR,T}$, $f_{u,SR,T}$, $E_{SR,T}$, and $\varepsilon_{u,SR,T}$, respectively, represent the yield strength, ultimate strength, elastic modulus, and ultimate strain of the rebars after high temperature T . $f_{y,SR,AT}$, $f_{u,SR,AT}$, $E_{SR,AT}$, and $\varepsilon_{u,SR,AT}$, respectively, represent the yield strength, ultimate strength, elastic modulus, and ultimate strain of the ambient temperature rebars corresponding to $f_{y,SR,T}$, $f_{u,SR,T}$, $E_{SR,T}$, and $\varepsilon_{u,SR,T}$.

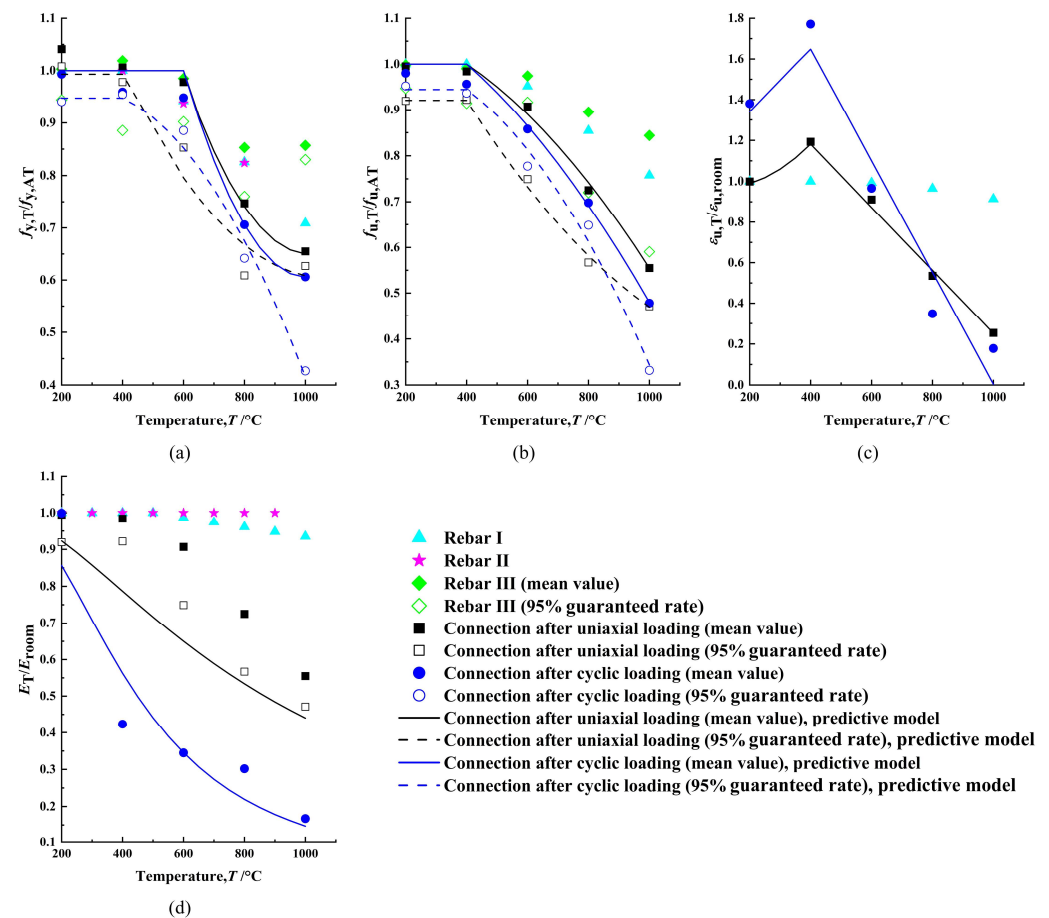


Figure 9. Temperature influence coefficients of rebars and connections after heating, water cooling and different loading schemes; (a) Yield strength; (b) Ultimate strength; (c) Ultimate strain; (d) Elastic modulus.

4.3.1. Strength

The temperature influence coefficient of connection strength changes with temperature (Figure 9a,b). Uniaxial and cyclic loads show a similar tendency, which initially does not vary with temperature but eventually declines drastically.

At lower temperatures, the connection strength is almost unaffected by temperature. The connection fails mostly owing to rebar fracture; hence, f_T/f_{AT} resembles rebars after heating. Therefore, the strength of the connection mainly depends on the rebar's mechanical properties, which are minimally affected by temperature at low temperatures. However, higher temperatures limit connection strength, as seen by f_T/f_{AT} being lower than rebars. High temperatures weaken the grouting material–rebar bond. Consequently, it is weaker than the ultimate strength of the rebar. At ambient temperature, the connection experiences rebar fracture, where f_{AT} represents the ultimate strength of rebars.

Based on the aforementioned analysis, a piecewise function is established as a quantitative model for the f_T/f_{AT} of GSC experiencing high temperature and water cooling. Finally, Formula (3) is selected as an appropriate calculation formula for f_T/f_{AT} .

$$f_T/f_{AT} = \begin{cases} A & (T_1 \leq T \leq T_2) \\ BT^2 + CT + D & (T_2 < T \leq T_3) \end{cases} \quad (3)$$

The quantile values of connection strength ($f_{y,T}/f_{y,AT}$ and $f_{u,T}/f_{u,AT}$) with a 50% (mean value) and 95% guaranteed rate were modeled. The results are presented in Figure 9a,b and Table 9.

Table 9. Parameters of the calculation formulas for $f_{y,T}/f_{y,AT}$ and $f_{u,T}/f_{u,AT}$ of GSCs after heating and water cooling.

Coefficients	Loading Scheme	Guaranteed Rate (%)	A	B	C	D	T ₁	T ₂	T ₃	R ₁
$f_{y,T}/f_{y,AT}$	Uniaxial loading	50	1.000	1.922×10^{-6}	−0.004	2.698	200	600	1000	0.99879
		95	0.993	8.701×10^{-7}	−0.002	1.598	200	400	1000	0.98790
$f_{u,T}/f_{u,AT}$		50	1.000	-4.813×10^{-7}	−73.100	1.104	200	400	1000	0.99997
		95	0.920	4.710×10^{-7}	−0.001	1.408	200	400	1000	0.99997
$f_{y,T}/f_{y,AT}$	Cyclic loading	50	1.000	2.422×10^{-6}	−0.005	3.044	200	600	1000	0.98182
		95	0.947	-1.027×10^{-6}	5.522×10^{-4}	0.891	200	400	1000	0.99676
$f_{u,T}/f_{u,AT}$		50	1.000	-4.765×10^{-7}	-1.995×10^{-4}	1.156	200	400	1000	0.98784
		95	0.944	-8.657×10^{-7}	2.111×10^{-4}	0.998	200	400	1000	0.99719

4.3.2. Ultimate Strain

Figure 9c shows that the temperature influence coefficient of the connection's ultimate strain changes with the temperature, increasing first and then decreasing with rising temperature. At lower temperatures, the ultimate strain of the connection increases with temperature, while the ultimate strength is almost unaffected. Hence, this phenomenon is mainly due to the degradation of the bonding performance between the rebar and the grouting material with the increase in temperature. At a higher temperature, the ultimate strain of the connection after heating decreases, while the bonding performance between the rebar and the grouting material and the ultimate strength of the connection both decrease. Therefore, the changing trend of the ultimate strain at this time is mostly affected by the ultimate strength. Additionally, the ultimate strain of the rebar changes little with the temperature increase. As a result, Equation (4) is selected as the calculation formula of the

connection's $\varepsilon_{u,T}/\varepsilon_{u,AT}$ after high temperature. The quantitative models for the average values of $\varepsilon_{u,T}/\varepsilon_{u,AT}$ are illustrated in Figure 9c and Table 10.

$$\varepsilon_{u,T}/\varepsilon_{u,AT} = \begin{cases} AT^2 + BT + C & (T_1 \leq T \leq T_2) \\ DT + E & (T_2 < T \leq T_3) \end{cases} \quad (4)$$

Table 10. The parameters of the calculation formula for $\varepsilon_{u,T}/\varepsilon_{u,AT}$ of GSCs after heating and water cooling.

Loading Scheme	A	B	C	D	E	T ₁	T ₂	T ₃	R ₁
Uniaxial loading	2.542×10^{-6}	-5.646×10^{-4}	1.000	−0.002	1.802	200	400	1000	0.99913
Cyclic loading	0	0.002	1.031	−0.003	2.744	200	400	1000	0.98305

4.3.3. Elastic Modulus

The temperature influence coefficient of the elastic modulus of the GSC is observed to decline nonlinearly with rising temperature, as depicted in Figure 9d. At lower temperatures, the elastic modulus of the connection decreases with rising temperature, while the yield strength of the connection remains largely unaffected. The observed occurrence may be ascribed to the deterioration in the adhesion between the grouting material and rebar at high temperatures. The elastic modulus of the connection reduces significantly as temperature rises, while the rebar modulus remains constant. This shows that while some of the rebar's elastic modulus can be recovered, most damage is irreversible. Based on these findings, Equation (5) is selected as an appropriate calculation formula for E_T/E_{AT} . The quantitative models depicting E_T/E_{AT} are illustrated in Figure 9d and Table 11.

$$E_T/E_{AT} = 1 / \left\{ A \left[1 + B(T/1000)^C \right] \right\} \quad T_1 \leq T \leq T_2 \quad (5)$$

Table 11. The parameters of the calculation formula for E_T/E_{AT} of GSCs after heating and water cooling.

Loading Scheme	A	B	C	T ₁	T ₂	R ₁
Uniaxial loading	0.998	1.276	1.683	200	1000	0.99042
Cyclic loading	0.997	5.831	2.191	200	1000	0.97992

4.3.4. Repercussions of Loading Scheme on Connection Performance After Heating and Water Cooling

After uniaxial loading or cyclic loading, the temperature influence coefficient of connection strength decreases significantly. The starting temperature of a precipitous strength fall is mostly determined by failure mode transformation temperature. Consequently, drawing the conclusion that the loading scheme exerts a negligible influence on the temperature point-of-connection failure mode transformation is warranted. The effect of cyclic loading on connection strength is more conspicuous at elevated temperatures compared with uniaxial loading. Furthermore, as the temperature rises, the gap between the two conditions widens. In general, the loading scheme has less impact than temperature. The temperature influence coefficient of the elastic modulus drops more than uniaxial loading when temperature rises after repeated tensile and compressive loading. Cyclic loading induces a more pronounced augmentation in ultimate strain at lower temperatures when compared with uniaxial loading. Nevertheless, the impact of both loading schemes on the ultimate strength of connections at high temperatures is negligible. This indicates that the bonding performance between rebars and grouting material is further compromised by

repeated tensile and compressive loading at elevated temperatures. At high temperatures, cyclic loading accelerates connection ultimate-strain decrease compared with uniaxial loading. The temperature influence coefficient of ultimate strain after repeated loading decreases compared with uniaxial loading at ultra-high temperatures.

5. Conclusions

This paper presents a supplementary study on the GSC's performance under repeated tensile-compressive loading after heating and water cooling. Based on this and previous studies, a predictive model is established to evaluate the mechanical behavior of the connections after heating and water cooling under uniaxial tensile and cyclic loading conditions with a certain level of reliability. The findings can aid PC structure resistance design and fire and earthquake safety identification. The key findings are as follows.

- (1) Two types of failure modes (rebar fracture and rebar pullout) occurred during the experiment. The two different failure types occur at 400 °C, the crucial heating temperature.
- (2) For GSCs after high temperatures followed by water cooling under cyclic loading, the yield strength and ultimate strength remain relatively constant at low temperatures. However, strength decreases as temperature rises. Additionally, the elastic modulus in the given region drops with temperature, while the ultimate strain rises and then falls.
- (3) When assessing connection performance at extreme temperatures, cyclic loading demonstrates a more dramatic degradation than uniaxial loading. Cyclic loading at high temperatures causes greater rebar pullout failure than unidirectional tensile loading.
- (4) The quantitative models with a 95% guaranteed rate for connections' yield strength and ultimate strength, as well as models with a 50% guaranteed rate for yield strength, ultimate strength, ultimate strain, and elastic modulus, are established.

Further study should be carried out to investigate the post-fire performance of GSCs under various loading situations (e.g., dynamic loads) and a more refined temperature classification (e.g., 300 °C or 500 °C). Furthermore, the aforementioned predictive models pertain exclusively to GSCs utilizing HRB400 rebars subjected to high temperatures followed by water cooling under uniaxial and cyclic loading conditions. The applicability of prediction models for GSCs will be broadened to encompass other grouting materials (e.g., UHPC), cooling methods (natural cooling), rebar types (HRB500), and other factors in future research.

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