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Seismic Damage Modeling of Corroded Bolted Steel Frame Structures in Atmospheric Environments: A Performance-Based Assessment

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Abstract: To facilitate a rigorous evaluation of damage progression in in-service steel frame structures subjected to seismic loading, a seismic damage model that integrates the effects of atmospheric corrosion has been developed. Corrosion-induced deterioration significantly influences the structural integrity of bolted steel frames, yet its impact on seismic performance remains inadequately quantified. In this study, a performance-based seismic damage assessment framework has been established, wherein corrosion-related degradation is incorporated into the structural damage evolution process. Drawing on an extensive review of domestic and international research, a refined damage index classification system has been formulated to characterize varying levels of structural impairment. To validate the proposed model, a seismic collapse simulation was conducted on a 1:4 scaled-down steel frame specimen, enabling a comprehensive analysis of damage accumulation over different service durations. The results confirm that the developed model accurately captures the progressive deterioration and collapse behavior of corroded steel frames under seismic excitation. This study provides a quantitative basis for assessing the post-earthquake residual load-bearing capacity of in-service bolted steel frame structures, offering critical insights for structural resilience evaluation and maintenance planning.

Keywords: Steel frame structures; Atmospheric corrosion; Seismic damage assessment; Bolted connections; Collapse simulation; Structural degradation

1 Introduction

The deterioration of steel structures over their service life can primarily be attributed to three key factors: inherent defects originating from fabrication and welding, corrosion-induced degradation due to environmental exposure, and sudden structural failure caused by natural disasters. Defects introduced during the fabrication and welding processes, including micro-cracks, porosity, and incomplete fusion, are inherently unavoidable and largely dependent on material properties, construction quality, and the skill level of personnel. However, due to their unpredictable nature, the quantitative assessment of damage resulting from such defects is beyond the scope of this study. In contrast, corrosion-related deterioration, particularly that induced by exposure to atmospheric conditions, represents a cumulative and inevitable process that progressively compromises the mechanical properties and structural integrity of steel components. Various environmental factors, including humidity, temperature fluctuations, and airborne pollutants, contribute to corrosion, with general atmospheric exposure being the most prevalent cause of long-term material degradation. Furthermore, steel structures are highly susceptible to abrupt damage induced by natural disasters, with seismic activity posing one of the most significant threats. Earthquakes have been widely recognized for their potential to induce severe structural failure, leading to abrupt changes in load-bearing capacity and overall stability. Unlike corrosion, which occurs progressively over time, seismic damage exhibits a probabilistic nature, as the occurrence and severity of an earthquake during a structure's lifespan remain uncertain. Given these distinct failure mechanisms, this study specifically focuses on assessing the effects of atmospheric corrosion and seismic loading on steel structures, as these factors collectively play a critical role in determining long-term structural performance and resilience.

Ordinary steel has very poor corrosion resistance, especially when exposed to environments with high humidity and corrosive media. According to the latest report by the National Association of Corrosion Engineers (NACE), the annual global cost of corrosion is estimated to be approximately \$2.5 trillion, accounting for 3.4% of the global Gross Domestic Product (GDP) [1]. Corrosion leads to a reduction in the net cross-sectional area of steel members, thereby decreasing the structural load-carrying capacity and reliability. Seismic events can cause damage to steel structures, including a reduction in stiffness and an increase in plastic deformation. During the 1995 Hanshin-Awaji Earthquake, in the severely affected central area of Kobe, over 1,000 steel-framed buildings were damaged, and more than 50 collapsed [2]. Most steel-framed buildings are continuously exposed to environmental factors throughout their service life. If an earthquake occurs under these conditions, the likelihood of structural collapse increases significantly. Wang et al. [3] conducted pseudo-static tests to investigate the seismic performance of H-shaped steel columns under general atmospheric conditions. They found that corrosion leads to premature entry into various stages, reduced load-bearing capacity, and a decreased yield deformation range. Zheng et al. [4] and Zhang et al. [5, 6] conducted experimental studies on the seismic performance of corroded steel frame columns in coastal atmospheric environments. The results showed that as the degree of corrosion increases, the bending capacity and ductility energy dissipation ability of the columns significantly decrease, and the degradation of strength and stiffness becomes more pronounced. Zhang et al. [7] argue that corrosion damage can reduce the seismic performance of steel structures, potentially leading to unexpected failure modes in high-seismicity regions. Therefore, they developed a detailed finite element model that accounts for the progression of corrosion damage and conducted nonlinear analyses under bidirectional cyclic loading. Di Sarno et al. [8] argue that atmospheric corrosion can significantly affect the performance of steel structures over long periods. It is crucial to evaluate the corrosion rate of the structures at different time intervals and the subsequent modifications to their dynamic performance.

Li and Kurata [9] proposed a probabilistic method based on an improved fishbone model for evaluating the seismic damage of beam-to-column connections in steel frames. Xiang et al. [10] proposed a direct method for assessing damage in tall steel frame structures under strong seismic loads, based on a mesoscale fracture model for inter-story drift measurements. Currently, most steel structure damage models used domestically and internationally are primarily designed to calculate seismic damage and do not consider the impact of environmental corrosion on structural damage. Given this, it is essential to develop a reasonable damage model to quantitatively assess the damage to steel structures under seismic loads after a certain service life in general atmospheric environments.

2 Seismic Damage Model for Steel Frames Considering Corrosion Damage in General Atmospheric Environments

2.1 Corrosion Model

According to the study [11], the primary corrosion process of uncoated carbon steel in atmospheric environments can be divided into three stages, as shown in Figure 1.

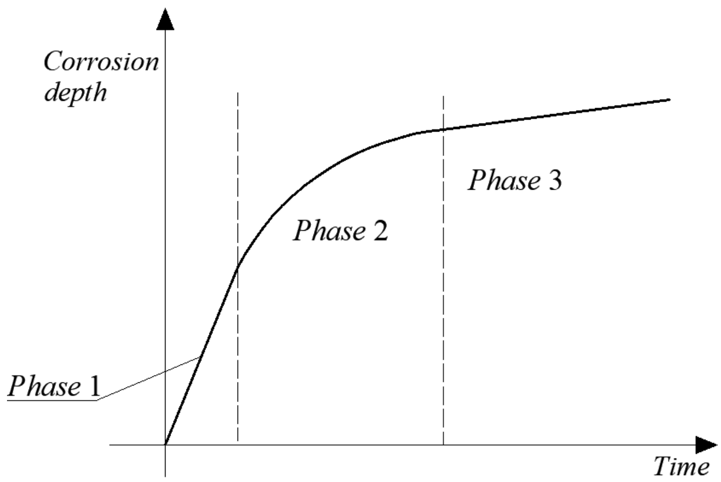

Figure 1. Atmospheric environmental corrosion process

The first stage is the initial corrosion phase of carbon steel in atmospheric environments. During this stage, the characteristic of corrosion is a linear increase in corrosion depth over time. Therefore, the corrosion model for this stage is:

$$y_t = at \tag{1}$$

where, y_t is the average corrosion depth, t is the corrosion time (represented by this symbol hereafter), and a is a coefficient representing the corrosion rate.

The second stage is the transitional phase where the corrosion rate of carbon steel slows down. This phase follows a pattern similar to that of a parabola. Therefore, the corrosion model for this stage is:

$$y_1 = At^2 + Bt + C \tag{2}$$

where, A, B and C are undetermined coefficients related to the corrosion rate.

After the first and second stages of corrosion, a certain thickness of rust layer has formed on the surface of the carbon steel. This rust layer can partially isolate the internal steel from the external environment, thus reducing the corrosion rate in the third stage. The corrosion model for this stage is similar to that of the first stage but with a smaller slope.

$$y_t = bt \tag{3}$$

where, b is an undetermined coefficient representing the corrosion rate, and $b < a$.

Based on corrosion data, the study [11] suggests that the first stage occurs within the range of 0 to 1 year, the second stage occurs within the range of 1 to 8 years, and the third stage begins after 8 years. To obtain a corrosion model suitable for carbon steel in typical domestic atmospheric environments, corrosion data for low-carbon steel under general atmospheric conditions can be utilized to determine the undetermined coefficients in Eqs. (1)-(3).

2.2 Damage Model

A representative seismic damage model is the one proposed by Park and Ang [12], which combines the maximum response displacement and cumulative energy dissipation linearly.

$$D_0 = \frac{\delta_m}{\delta_u} + \frac{\beta}{Q_v \delta_u} \int dE \tag{4}$$

where, δ_u and δ_m are the ultimate displacement and maximum displacement of the structure or component, respectively; dE is the incremental hysteretic energy dissipation; Q_y is the yield strength of the structure or component; and β is the energy influence coefficient.

The corrosion pattern of ordinary steel in general atmospheric environments is a combination of pitting corrosion and uniform corrosion [13]. However, when quantifying the impact of corrosion damage on the performance of steel, pitting corrosion is often disregarded due to its random distribution, depth, and other characteristic parameters that are difficult to quantify. Therefore, this study assumes that only uniform corrosion occurs. For steel components undergoing uniform corrosion, the primary effect of corrosion on the load-bearing capacity and reliability of the components is the reduction in cross-sectional area.

The two-parameter model proposed by Park and Ang [12], which combines deformation and energy, effectively represents the failure mechanisms of structures. Based on this model, this study considers the impact of corrosion on structural damage for steel structures after a certain service life in general atmospheric environments. A seismic damage model for steel frames that incorporates corrosion damage is established:

$$D = \alpha \frac{A_t}{A_0} + D_0 \tag{5}$$

where, A_0 is the designed cross-sectional area of the component; A_t is the corroded cross-sectional area of the component after a certain service life; and α is the corrosion damage influence coefficient. The damage index D has the following two characteristics:

(1) The value of D ranges from 0 to 1. When D=0, it indicates that the structure or component is intact. When D =1, it means that the structure or component is completely damaged.

(2) The damage index D is an increasing function, indicating that the damage to the structure or component progresses irreversibly.

(3) Eq. (5) is calculated by first computing the first term $\alpha A_t/A_0$ followed by the second term D_0 .

Eq. (5) exhibits clear time-dependent behavior. The physical significance of the equation can be described as follows:

(1) In the early stages of use, when the service life is 0 years, the corrosion rate of the component cross-section is 0. At this point, the damage model is consistent with the Park damage model, which assumes that all structural damage is caused by earthquakes.

(2) As the structure is used, the corrosion rate of the component cross-section increases over time. Consequently, as time progresses, the probability of structural collapse under the same seismic event increases, and the proportion of earthquake-induced damage in the damage model decreases.

(3) If the corrosion of the components is very severe, the structure may already be damaged even without seismic activity, in which case the second term on the right-hand side of the equation equals 1.

The designed cross-sectional area A_0 and the corroded cross-sectional area A_t of the structure after a certain service life t in a general atmospheric environment can be expressed as:

$$A_0 = b \times h - (b - t_w) \times (h - 2t_0) \tag{6}$$

$$A_t = 2\left[y_t \times (b - 2y_t) + 2y_t \times t_a + (b - 2y_t - t_w) \times y_t\right] + 2y_t\left[h - 2\left(t_a - y_t\right)\right] \tag{7}$$

In the above equation, A_t is only related to the average corrosion depth y_t, b, h, t_w and t_a represent the flange width, section height, web thickness, and flange thickness of the H-shaped steel section, respectively, as shown in Figure 2.

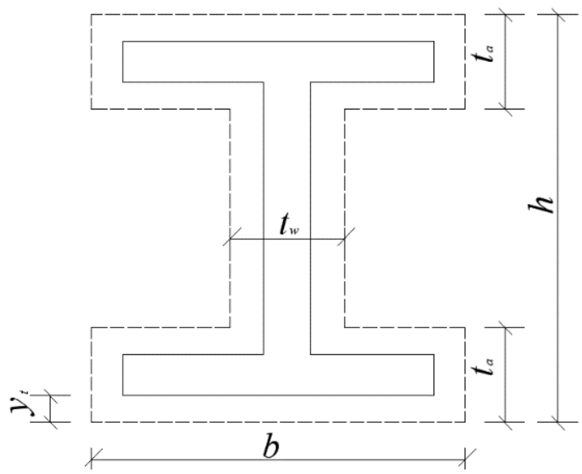

Figure 2. Cross-section of an H-shaped steel section with a corrosion depth of y_t

2.3 Determination of Parameters

β is the energy influence coefficient, which needs to be determined through experiments. Based on extensive testing, Park and Ang [12] found that the energy influence coefficient β for concrete structures is influenced by factors such as the shear span ratio, axial compression ratio, reinforcement ratio, and stirrup ratio, and typically ranges from 0.3 to 0.12, with a common value of around 0.15. Considering that steel structures have a stronger energy dissipation capability compared to reinforced concrete structures, the energy influence coefficient β in this study is taken as 0.3 [14].

As an energy influence coefficient, β is an empirical parameter calibrated through a large number of cyclic loading tests on structures or components, such as hysteresis tests on reinforced concrete beams and columns. Researchers used regression analysis to correlate the observed damage phenomena (such as stiffness degradation and strength loss) in the experiment with the energy dissipation term in the model, in order to determine the reasonable range of values for β. Based on extensive experiments conducted by Park and Ang [12], it is believed that the energy influence coefficient a of concrete is influenced by the shear span ratio, axial compression ratio, reinforcement ratio, and reinforcement ratio, and is generally between 0.3 and 0.12, often around 0.15. In the seismic performance evaluation of steel frames using FEMA-355D, it is recommended to combine the Park Ang model, with a β value range of 0.15 0.3 (based on hysteresis test data of steel beam column nodes) [14]. Lignos and Krawinkler [15] conducted cyclic loading tests on a large number of steel frame nodes, calibrated the value of β as 0.2$\sim$0.3, and discussed the influence of parameters on the damage index. The energy influence coefficient β in this article is taken as 0.3 according to reference [15].

As the corrosion depth increases, the reliability of steel components gradually decreases. Even with minor seismic activity or no seismic activity, steel components may fail. If steel components fail solely due to corrosion, the first term on the right-hand side of Eq. (5) must equal 1, in which case α= A_0/A_t. To determine the corrosion rate A_t/A_0 corresponding to the failure of steel components, it is necessary to first define the levels of corrosion severity for steel components. Referencing the studies [13, 16], the classification of corrosion severity for steel structures is detailed in Table 1.

This study considers that steel components are deemed to be damaged when the corrosion severity reaches Grade E. At this level, the corrosion area of the component is approximately 50%, i.e., A_t/A_0=1/2. By setting α=2, the structural damage index D becomes 1. This boundary condition determines that α=2 in Eq. (5).

Table 1. Classification of corrosion degree of steel structure

Corrosion Severity Levels	Condition	Phenomenon
Grade A	Good	The component is essentially free from corrosion; individual components may have a few rust spots.
Grade B	Local Corrosion	The component has a few rust spots or corrosion in edges, corners, gaps, and hidden parts.
Grade C	Moderately Severe	The component has localized corrosion.
Grade D	Severe	The corrosion area of the component is around 40%.
Grade E	Extremely Severe	The component has either been taken out of service or requires reinforcement. The corrosion area of the component is around 50%.

2.4 Structural Layer Damage Model

Compared to welded connections, which are prone to brittle failure under seismic loads [2], bolted connections maintain good connection status under seismic loads and do not exhibit severe damage [17]. Therefore, to simplify the calculation of layer damage, the influence of bolted connection node damage on layer damage is not considered. That is, the layer damage calculation formula only includes the damage to beams and columns in that layer.

To measure the proportion of beam and column component damage in the overall layer damage, weight coefficients $\eta_{ji,b}$ and $\eta_{ki,c}$ are defined for beams and columns, respectively. The calculation formulas for the single-layer beam and column component damage weight coefficients $\eta_{ji,b}$ and $\eta_{ki,c}$ are as follows:

$$\eta_{ji,b} = \frac{D_{ji,b}}{\sum_{j=1}^{n} D_{ji,b} + \sum_{k=1}^{n+1} D_{ki,c}} \tag{8}$$

$$\eta_{ki,c} = \frac{D_{ki,c}}{\sum_{j=1}^{n} D_{ji,b} + \sum_{k=1}^{n+1} D_{ki,c}} \tag{9}$$

where, $\eta_{ji,b}$ and $\eta_{ki,c}$ are the weight coefficients of the j-th frame beam and the k-th frame column in the i-th layer, respectively; $D_{ji,b}$ and $D_{ki,c}$ are the damage values of the j-th frame beam and the k-th frame column in the i-th layer, respectively; $\sum_{j=1}^{n} D_{ji,b}$ and $\sum_{k=1}^{n+1} D_{ki,c}$ are the total damage of frame beams and frame columns in the i-th layer, respectively.

The layer damage model for steel frame structures in this study is defined as follows:

$$D_i = \sum_{j=1}^{n} \eta_{ji,b} D_{ji,b} + \sum_{k=1}^{n+1} \eta_{ki,c} D_{ki,c} \tag{10}$$

where, D_i is the damage value of the i-th layer.

2.5 Overall Structural Damage Model

When analyzing the seismic performance of a structure, it is more meaningful to study the overall damage state of the structure. When assessing the damage to the structure, the overall damage index of the structure can be used to represent it. To accurately express the contribution of layer damage to the overall structural damage, Park and Ang [12] proposed a weighted average method for calculating the overall structural damage, as shown in the following equation:

$$D = \sum_{j=1}^{N} \lambda_i D_i \tag{11}$$

The value of λ_i is determined using the method proposed in the study [12].

$$\lambda_i = \sqrt{\gamma_i^2 + \mu_{D_i}^2} \tag{12}$$

$$\gamma_i = \frac{1}{N^{1/2}} \tag{13}$$

$$\mu_{D_i} = \frac{D_i}{\sum_{i=1}^{N} D_i} \tag{14}$$

where, γ_i is the position weight coefficient of the i-th layer, and μ_{D_i} is the damage weight coefficient of the i-th layer of the structure.

3 Determination of Seismic Damage Grades Based on Damage Indices

To evaluate the seismic capacity of steel frame structures with different service lives, it is necessary to determine their seismic damage grades and the corresponding damage indices for those grades. Currently, there is no scientifically unified standard in the field of structural engineering for the damage grades of post-earthquake components and structures, as well as the corresponding threshold values of damage indices. Researchers have provided threshold values for damage indices at different damage grades based on their own proposed damage calculation models. Referring to the damage index ranges provided by domestic and international scholars [12, 14], and considering the characteristics of the damage model presented in this study, the damage index ranges corresponding to different damage grades for steel structures are defined, as shown in Table 2.

Table 2. Damage index corresponding to different damage level

Seismic Damage Grades	Damage-State	Damage Index D	Supporting Evidence (Experiments/Literature)
Essentially Intact	The structural function is not affected	$0 < D \leq 0.25$	Reinforced concrete test [12]
Slight-Damage	Non load bearing components require minor repairs	$0.25 < D \leq 0.45$	Energy dissipation model [18]
Moderate Damage	The load-bearing components need to be repaired	$0.45 < D \leq 65$	Seismic damage statistics [19]
Severe-Damage	Functional loss of structural components	$0.65 < D \leq 0.9$	FEMA-355D steel frame collapse case [14]
Collapse	Beyond repair	$D > 0.9$	Observation of limit state of steel frame vibration table test [20]

4 Numerical Example

4.1 Finite Element Model

To verify the correctness and rationality of the damage model presented in this study, three scaled-down steel frame models with a scale ratio of 1/4 were analyzed using SAP2000. These models represent service ages of 0 years, 1 year, and 8 years, respectively, under general atmospheric conditions. The finite element model is shown in Figure 3. The structural model does not consider the damage to beam-to-column bolted connections. All parameters of the 1/4 scaled model structure were determined based on the consistent similarity rate derived by Zhang [21], a researcher at the Institute of Engineering Mechanics of the National Seismological Bureau. The seismic analysis results of the scaled structure have a high similarity with the prototype structure in terms of overall dynamic response and failure mode, but significant errors may be introduced by local details and nonlinear behavior. To ensure the reliability of the analysis, it is necessary to strictly follow the scaling principle, verify through a combination of experiments and numerical simulations, and conduct sensitivity analysis on key parameters.

The steel frame structure consists of 6 stories, with two spans in both the X and Y directions. Each span in the X direction is 1.5 m long, and each span in the Y direction is 1.0 m long. The height of the ground floor is 1.05 m, and the height of the remaining floors is 0.9 m each. The steel used is Q235. The frame beams are made of hot-rolled I-beams with a size of 10. For the frame columns, HW150×150×7×10 is used for the 1st and 2nd floors, HW125×125×6.5×9 is used for the 3rd and 4th floors, and HW100×100×6×8 is used for the 5th and 6th floors. The floor load is determined to be 17.5 kN/m^2, and the roof load is 8.7 kN/m^3. The El Centro earthquake wave is used as the ground motion for time history analysis, and the loading conditions are listed in Table 3.

The average corrosion rates of carbon steel for service ages of 1 year and 8 years under general atmospheric conditions (i.e., a and b in Eqs. (1) and (3)) are selected from the data for Beijing in the study [22]. The values are $a = 0.034$ mm/year and $b = 0.011$ mm/year. The coefficients A, B, and C in Eq. (2) are also determined based on the corrosion data for Beijing in the study [22], with $A = -0.0015$, $B = 0.0225$ and $C = 0$.

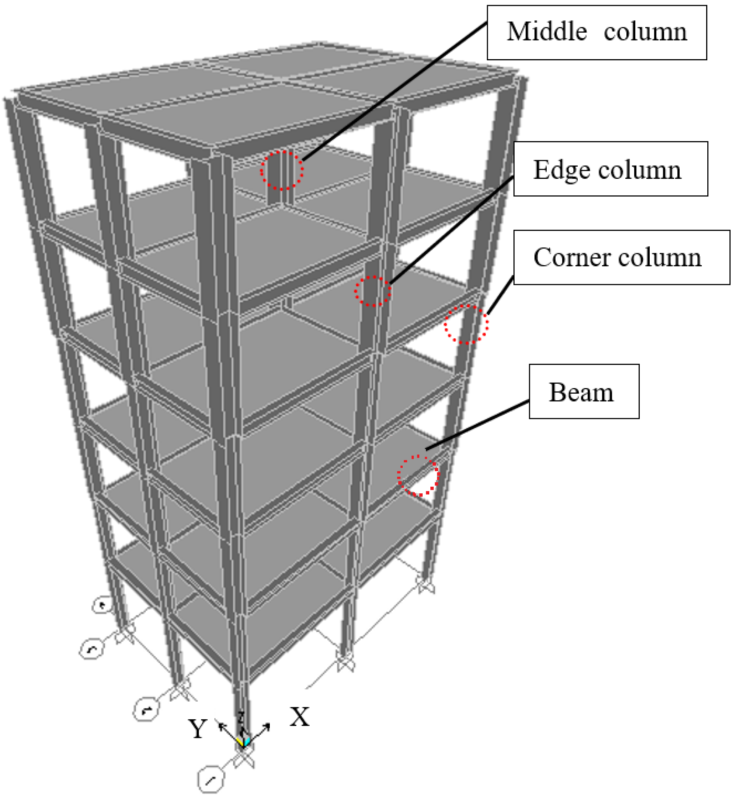

Figure 3. Structural model

Table 3. Loading conditions of model and the peak value of earthquake acceleration

Load Case Number	Intensity	Seismic Excitation	Seismic Input Value (g)		Notes
			Model X Direction	Model Y Direction	
1	Rare Event at Intensity-8	El-Centro	0.37	0.4	Bi-directional Earthquake
2	Rare Event at Intensity 9	El-Centro	0.6	0.62	Bi-directional-Earthquake
3		El-Centro	1.2	1.42	Bi-directional Earthquake

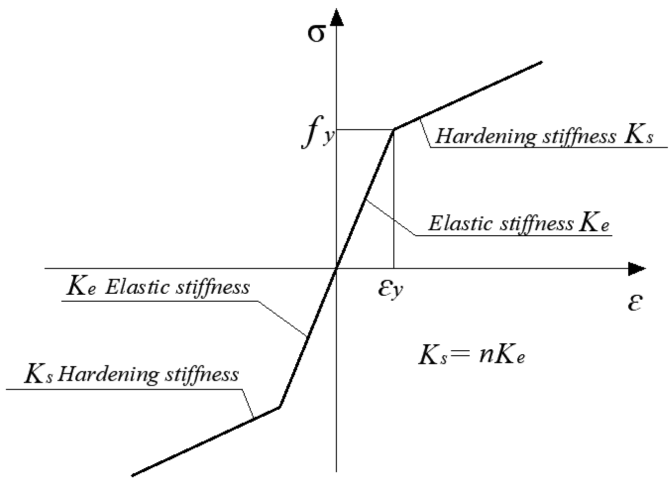

Figure 4. Bilinear hardening constitutive model

The material constitutive model for the steel used in the structural model is a bilinear hardening model, as shown in Figure 4. The material parameters for the uncorroded steel are listed in Table 4, where the density is 7850 kg/m^3

and the Poisson's ratio is 0.3.

Table 4. Material properties of steel

	K_e/MPa	f_y/MPa	n
Beam	2.06×10^5	245	0.03
Column	2.06×10^5	300	0.03

4.2 Results Analysis

Figures 5-7 show the variation of damage values over time for the first-floor beams and columns of steel frame structures with service ages of 0, 1, and 8 years under the third working condition (El-Centro seismic wave) in a general atmospheric environment. Table 5 presents the overall damage values of structures with different service ages under various load conditions.

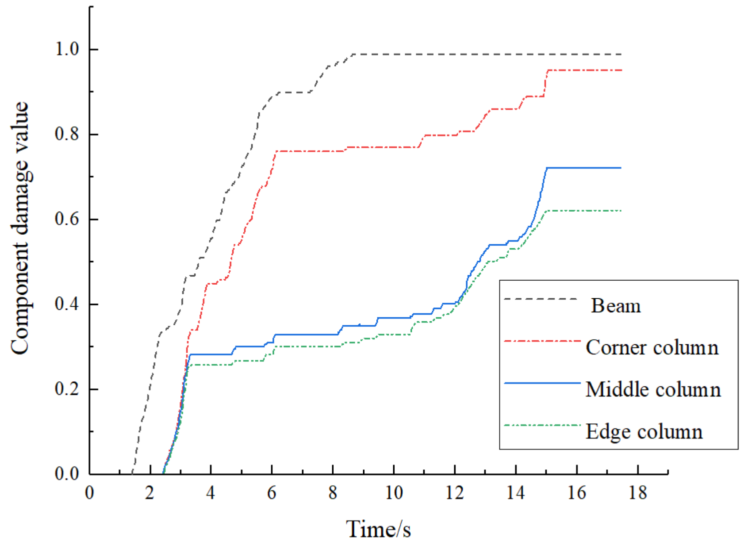

Figure 5. The damage development of the first-floor beams and columns of steel frame structure with the service age 0 under third load condition

Table 5. The overall damage value of steel frame structure with different service age in different load condition

Load Case Number	Service Life of the Structure in Atmospheric Environment (Years)		
	0	1	8
1	0.17	0.18	0.22
2	0.28	0.31	0.35
3	0.77	0.8	0.9

Based on the data from Figures 5-7 and Table 5, the damage analysis for structures with different service ages is as follows:

(1) Service age of 0 years (no corrosion)

The damage is entirely caused by seismic loads. The time difference between beam failure (9 seconds) and column failure (14.5 seconds) reflects the strong column-weak beam design philosophy. Under Working Condition 3, the overall damage value D=0.77 (severe damage) indicates that the uncorroded structure retains some redundancy and does not collapse.

(2) Service age of 1 year (mild corrosion)

Corrosion causes initial damage (D=0.05, Figure 6), weakening the elastic-stage load-bearing capacity. The beam failure time advances to 8.5 seconds, and column failure time shortens to 12 seconds (compared to Figure 5), showing that corrosion accelerates plastic hinge formation. Under Working Condition 3, D=0.8, nearing the collapse threshold (D=0.9), indicating that mild corrosion significantly reduces seismic resilience.

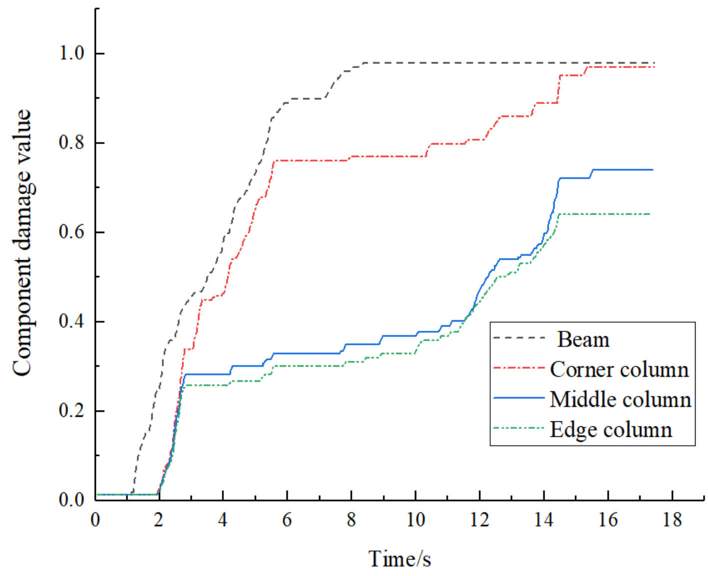

Figure 6. The damage development of the first-floor beams and columns of steel frame structure with the service age 1 under third load condition

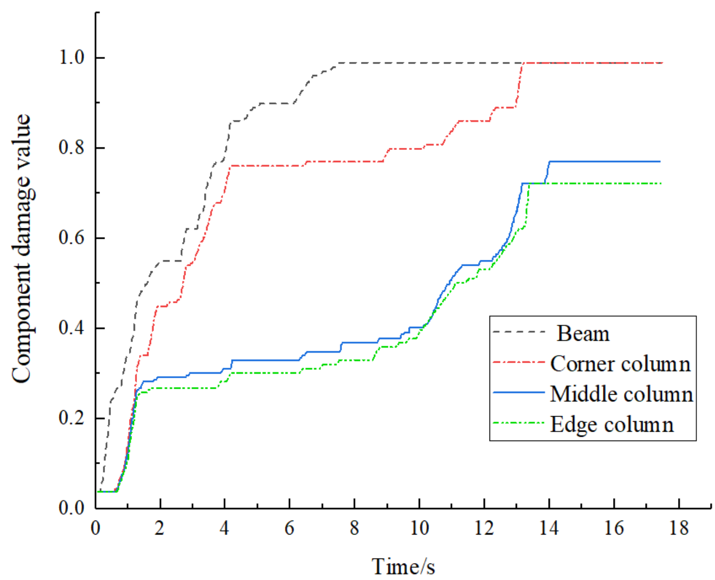

Figure 7. The damage development of the first-floor beams and columns of steel frame structure with the service age 8 under third load condition

(3) Service age of 8 years (severe corrosion)

Corrosion leads to initial damage (D=0.15, Figure 7), with some components (e.g., edge columns, D=0.2) already entering the plastic stage. After seismic input, corrosion-weakened areas (e.g., welded joints) rapidly fail, triggering collapse at D=0.9 (Working Condition 3). The failure time is 40% shorter than that of the 0-year structure.

Table 5 shows that under seismic intensity equivalent to a rare earthquake of 8 degrees, structures with service ages of 0, 1, and 8 years remain in a slight damage state. At 9 degrees, all structures enter a moderate damage state. Under 4× El-Centro wave intensity, structures aged 0 and 1 year suffer severe damage, while the 8-year structure collapses, highlighting corrosion's detrimental impact on ultimate bearing capacity and seismic performance. These results demonstrate that under identical seismic loads, the overall structural damage increases with service age, reflecting corrosion's influence on structural damage and validating the effectiveness and rationality of the proposed damage model.

4.3 Coupled Damage Mechanism of Corrosion and Seismic Action

Based on the above research findings, the coupled damage mechanism of corrosion and seismic action is further analyzed. The synergistic effect of corrosion and seismic action exacerbates the damage to steel frame structures through the following pathways:

Reduction in effective cross-sectional area: Corrosion of steel components leads to a decrease in the effective cross-sectional area (e.g., corrosion thickness reaching 0.1 mm/year), resulting in significant reductions in bending stiffness and yield strength.

Prolonged natural vibration period: After corrosion, the natural vibration period of the structure increases (as shown in Case 3 of Table 5, where damage values rise with service age). This makes the structure more prone to resonance with the spectral characteristics of seismic motions (e.g., El-Centro wave energy concentrated in 1-2 Hz), thereby amplifying displacement demand (δ_m/δ_u).

5 Conclusions

This study considers the damage to steel frame structures from both general atmospheric corrosion and earthquakes, establishing a seismic damage model for steel frame structures that accounts for general atmospheric corrosion damage. The model uses a corrosion damage influence factor to adjust the contribution of corrosion damage to the overall component damage. The following conclusions are drawn from the analysis:

(1) The damage model established in this study is conceptually clear and physically meaningful. It comprehensively considers the two main factors causing damage to steel frames, and the overall model exhibits time-varying characteristics. It is effective throughout the entire service life of the structure and can assess the seismic capacity of the structure at various stages.

(2) The analysis of the overall damage results of the example structure shows that the damage index ranges corresponding to different damage grades of steel frame structures, as defined in this study, have good practicality.

(3) Corrosion damage reduces the seismic capacity of the structure. Under the same seismic load, the overall damage value of the structure increases with the increase in section corrosion rate. This indicates that structural damage caused by atmospheric corrosion cannot be ignored, as it directly affects the safety of the structure during its use. This further validates the effectiveness and rationality of the damage model proposed in this study for evaluating the damage development of in-service steel frame structures under strong earthquakes.

(4) The limitation of this study is that it ignores the influence of node damage on interlayer damage and does not consider the impact of pitting corrosion on the seismic performance of steel structures. The next step will focus on studying the damage development mode of bolted connections under earthquake action, as well as the influence of local pitting corrosion on the properties of steel materials, local and overall structural performance.

This study examined the damage sustained by steel frame structures due to both general atmospheric corrosion and seismic events, leading to the development of a seismic damage model that explicitly accounts for corrosion-induced deterioration. The model incorporated a corrosion damage influence factor to quantitatively adjust the contribution of corrosion to the overall structural degradation. Based on the analysis, the following conclusions have been drawn:

(1) The proposed damage model is conceptually well-defined and physically interpretable. By integrating the two primary mechanisms of structural degradation—seismic loads and atmospheric corrosion—the model effectively captures the time-dependent nature of structural deterioration. Its applicability extends across the entire service life of the structure, enabling the assessment of seismic performance at various stages of degradation.

(2) The evaluation of an illustrative case study has demonstrated the practical validity of the damage index ranges established in this study for categorising different levels of structural damage in steel frames. These indices provide a reliable basis for assessing structural integrity and informing maintenance strategies.

(3) Atmospheric corrosion has been shown to significantly reduce the seismic capacity of steel frame structures. Under identical seismic loading conditions, structural damage increases as the section corrosion rate rises. This underscores the necessity of accounting for corrosion effects in seismic vulnerability assessments, as corrosion-induced deterioration directly compromises structural safety. The findings further confirm the validity and effectiveness of the proposed model in characterising damage progression in in-service steel frame structures subjected to strong earthquakes.

(4) Certain limitations remain in the present study. Specifically, the influence of joint deterioration on inter-story damage propagation has not been considered, nor has the effect of localised pitting corrosion on the seismic performance of steel components. Future research will focus on refining the model by incorporating the degradation mechanisms of bolted connections under seismic loading and investigating the impact of localised pitting corrosion on material properties, component behaviour, and overall structural response.

By addressing these limitations, a more comprehensive and accurate framework for evaluating the long-term seismic resilience of corrosion-affected steel structures can be developed. This will contribute to enhanced predictive capabilities and more effective mitigation strategies in the field of structural engineering.

Author Contributions

Conceptualization, P.W.; methodology, P.W. and X.W.; software, P.W. and Y.G; validation, X.W.; formal analysis, Y.G.; investigation, J.Y.; resources, P.W.; writing—original draft preparation, X.W.; writing—review and editing, P.W.; visualization, W.C. All authors have read and agreed to the published version of the manuscript.

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Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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