Effect of Metal Corrosion on the Maximum Deflection of I-Section Steel Beams subjected to Sudden Short-Duration Constant Force

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ABSTRACT

This paper aims to determine the effect of metal corrosion on the maximum deflection of I-section steel beams subjected to sudden constant force in a short duration. To calculate this type of deflection, a model was developed and subsequently combined with a metal corrosion model, considering the beam's cross-section and stiffness reduction. A series of investigations of the maximum steel beam deflection in different corrosive environments were carried out. The results showed that the maximum deflection of I-section steel beams varied from 6.63% (in rural environments) to 29.62% (in marine environments) after 100 years. These findings highlight the importance of considering long-term corrosion effects when designing steel structures, particularly those exposed to sudden and sustained forces in a short time.

Keywords-steel beam; sudden constant force; environment; effective corrosion; maximum steel beam deflection

I. INTRODUCTION

Steel beams are commonly used in bridges and building structures because of their high load-bearing capacity and design flexibility. However, they can lose their cross-sectional area and stiffness when exposed to corrosive environments. This can increase beam deflection, posing a safety risk, especially when the former are subjected to sudden, continuous forces over short time periods. The impact of metal corrosion on steel beams is a fascinating area of research that has garnered attention from scientists worldwide. Corrosion diminishes steel's bearing capacity and significantly affects the structures' safety and service life, particularly those of steel beams.

Numerous studies have contributed to a better understanding of this issue. For example, research on the reliability of steel girder bridges with dependent corrosion development has explored the relationship between the corrosion process and the extent of deterioration in bridge reliability [1]. The effect of corrosion severity on the ultimate strength of a steel box girder was analyzed, demonstrating how different corrosion levels affect the ultimate load-bearing capacity of box girder structures [2]. Furthermore, regarding the influence of copula on time-varying reliability related to continuous time-varying stochastic processes, mathematical methods were utilized to model the reliability variation of steel structures over time [3]. The time-varying reliability profile for steel girder bridges further delves into this aspect, providing models to predict the reliability change of steel bridges throughout their life cycle [4]. Notably, a reliability analysis of bridge girders was conducted based on Gaussian copula models and monitoring data. Accurate monitoring data were employed along with mathematical models to assess the condition of steel girder bridges more accurately [5]. The lifecycle-based maintenance strategy was deployed for bridge networks affected by corrosion, considering the correlation between these networks' load-bearing capacity. Certain maintenance options were proposed based on the relationship between the bridges in a network, helping optimize the maintenance strategy [6]. These studies have made significant contributions to developing optimal solutions for extending the lifespan and ensuring the safety of construction structures, particularly steel girder bridges, against the adverse effects of metal corrosion. Corrosion is a complex phenomenon typically represented through mathematical formulations. A widely used corrosion model, proposed in [7], accounts for various environmental conditions, including marine, urban, and rural areas. This model has been applied in multiple studies, such as in [8], demonstrating its consistency and high reliability.

II. THEORETICAL FOUNDATIONS

A. The Maximum Steel Beam Deflection subjected to Sudden Constant Force in a Short Duration

It is assumed that before the force is applied, the system is in equilibrium with no deflection or oscillation ($y_0 = 0, v_0 = 0$). When a constant force is suddenly applied, according to [9], the equation of motion in this case is:

$$y = \frac{\omega^2 \delta_{1P}}{\omega_1} \int_0^t P(\tau) e^{-\alpha(t-\tau)} \sin \omega_1 (t-\tau) d\tau \qquad (1)$$

This force is classified as a dynamic force; however, it behaves similarly to an excitation force with a constant magnitude P(t) = P, as shown in Figure 1, which is applied to the beam for a short duration and then removed. Unlike an impact force, which depends on the height and magnitude of the impact, this force is specifically considered a braking force caused by transportation.

Since the force is constant, $P(\tau) = P = \text{const}$, hence:

$$y = \frac{\omega^2 \delta_{1P} P}{\omega_1} \int_0^t e^{-\alpha(t-\tau)} \sin \omega_1 (t-\tau) d\tau \qquad (2)$$

If the force is applied directly to the mass, the equation has the form:

$$\delta_{1P} = \delta_{11} \text{ and } \omega^2 \delta_{1P} = \omega^2 \delta_{11} = {}^{1}\!/_{M} \qquad (3)$$

The equation of motion in this case is expressed as:

$$y = \frac{P}{M\omega_1} \int_0^t e^{-\alpha(t-\tau)} \sin \omega_1 (t-\tau) d\tau \qquad (4)$$

By solving the integral, we obtain:

$$y = \frac{P}{M\omega_1} \cdot \frac{\omega_1}{\alpha^2 + \omega_1^2} \times$$

$$\left[1 - e^{-\alpha t} \left(\cos \omega_1 t + \frac{\alpha}{\omega_1} \sin \omega_1 t\right)\right] \qquad (5)$$

Let $\omega = \sqrt{\alpha^2 + \omega_1^2}$, the equation can be rewritten as:

$$y = \frac{P}{M\omega^2} \cdot \left[1 - e^{-\alpha t} \left(\cos \omega_1 t + \frac{\alpha}{\omega_1} \sin \omega_1 t\right)\right] \qquad (6)$$

On the other hand, according to [9], $\frac{P}{M\omega^2} = P\delta_{11}$, which represents the deflection of the mass M caused by a static force P. The equation becomes:

$$y = y_t \cdot \left[1 - e^{-\alpha t} \left(\cos \omega_1 t + \frac{\alpha}{\omega_1} \sin \omega_1 t\right)\right] \qquad (7)$$

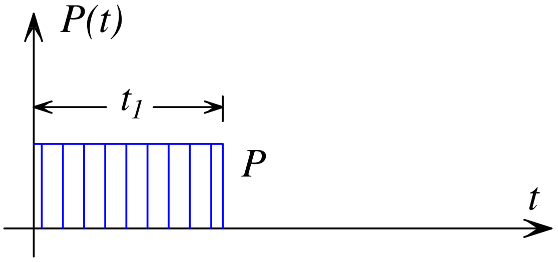

Fig. 1. Illustration of a constant force in a short duration.

Now, let us consider a constant force P suddenly applied to a beam. After a period t_1, this force is suddenly removed, as portrayed in Figure 1. Once the load is removed, the system oscillates freely, starting from time $t = t_1$, with initial deflection $y_{t_1} = y_t(1 - \cos \omega t_1)$, and initial velocity $\dot{y}_{t_1} = y_t \omega \sin \omega t_1$.

According to [14], the free oscillation equation for $t > t_1$, with initial conditions $y_0 = y_{t_1}$ and $v_0 = \dot{y}_{t_1}$, is:

$$y = y_t\, [\cos \omega(t - t_1)$$

$$- \cos \omega t_1 (\cos \omega t \cdot \cos \omega t_1 + \sin \omega t \cdot \sin \omega t_1) +$$

$$\sin \omega t_1 (\sin \omega t \cdot \cos \omega t_1 + \cos \omega t \cdot \sin \omega t_1)\,] \qquad (8)$$

Or:

$$y = y_t(\cos \omega(t - t_1) - \cos \omega t) \qquad (9)$$

The final vibration equation is written as:

$$y = 2y_t \sin \frac{\omega t_1}{2} \cdot \sin \omega \left(t - \frac{t_1}{2}\right) \qquad (10)$$

The maximum deflection is:

$$y_{\max} = 2y_t \sin \frac{\omega t_1}{2} = 2y_t \sin \frac{\pi t_1}{T} \qquad (11)$$

This expression calculates the maximum deflection of a beam subjected to a suddenly applied concentrated load over a short period. It is combined with the corrosion model and forms of corrosion in the atmospheric environment to investigate the maximum deflection of steel beams, taking into account metal corrosion.

B. Metal Corrosion Model and Steel Beam Corrosion Form Model

The empirical metal corrosion model, or power-law model, has been developed over the years based on research of many scientists in the field of corrosion. It describes the thickness loss of metals in different environments (e.g., atmospheric, seawater, and industrial environments). The equation describing the thickness loss is:

$$d(t) = A \cdot t^B \qquad (12)$$

where $d(t)$ is the thickness of the corroded metal layer after time t, A and B are the empirical parameters that characterize the environmental conditions and the type of material, and t is the time since the metal was exposed to the corrosive environment.

Equation (12) represents the thickness loss rate of metal with time. The model's accuracy depends on the constants: A, which represents the initial corrosion rate, and B, which reflects the time-dependence of the corrosion rate. Therefore, this study used the constants A and B proposed in [7] and displayed in Table I. This proposal's reliability has been verified in [8, 10-12].

TABLE I. COEFFICIENTS A AND *B* FOR DIFFERENT ENVIRONMENTAL CONDITIONS

Environment					
Rural		Urban		Marine	
A = 34.0	B = 0.64	A = 80.2	B = 0.59	A = 70.6	B = 0.79

The scenario protective coating is expected to be effective for the first 15 years for rural environments, 10 years for urban areas, and 5 years for marine environments, meaning there should be no corrosion before this period. Figure 2 outlines the corrosion rates for three various environmental conditions.

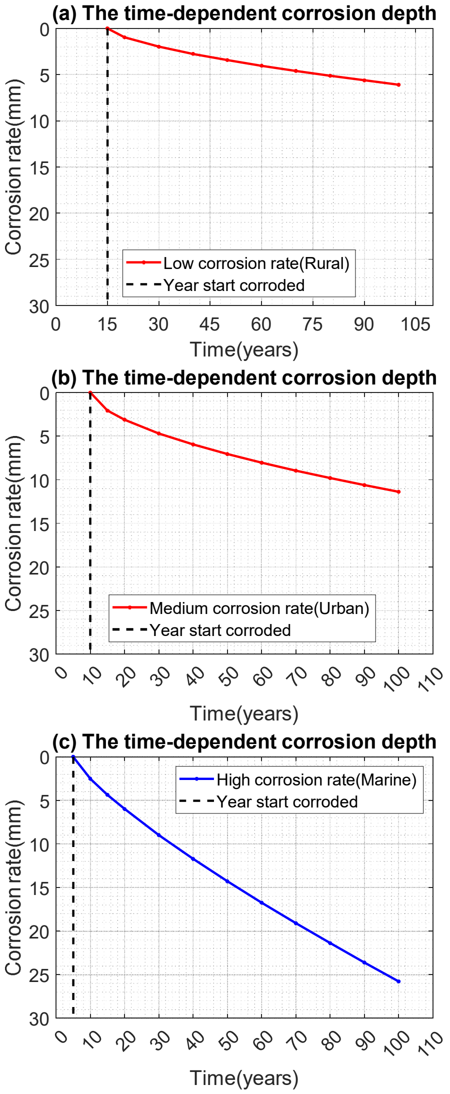

Fig. 2. The time-dependent corrosion depth in various environments.

C. *Steel Beam Corrosion Form Model*

Steel structures often experience localized corrosion under the influence of corrosive agents. Authors in [13] proposed a form of localized corrosion when studying corroded steel beams, as can be seen in Figure 3. Localized corrosion is observed on the steel beam, primarily concentrating on specific points on the cross-section. This results in increased beam deflection, especially at locations where the material thickness has significantly decreased. A concentrated load over a short duration was applied to the corroded beam to investigate the maximum deflection of steel beams under a sudden force. The study used the corrosion model introduced in (12) and the above corrosion form to predict corrosion development over time. Through this approach, a quantitative analysis of corrosion impact on the maximum deflection of the steel beam after 100 years was conducted.

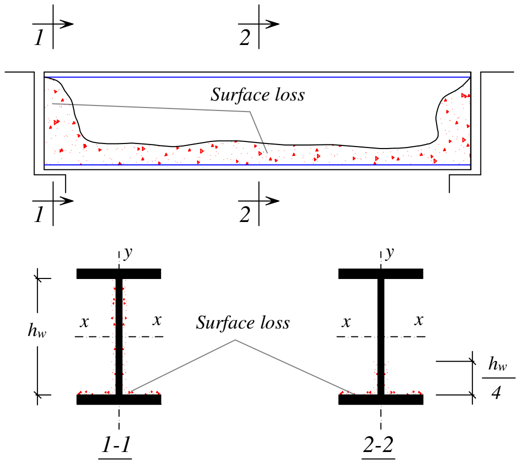

Fig. 3. Corrosion form of steel beam.

III. EFFECT OF METAL CORROSION MAXIMUM STEEL BEAM DEFLECTION SUBJECTED TO SUDDEN CONSTANT FORCE IN A SHORT DURATION

A. *Calculation Procedure*

The corrosion model proposed in [7] is incorporated to determine the maximum deflection of corroded steel beams. The following steps can be implemented:

- Step 1. Prepare the calculation data.
- Step 2. Determine the corrosive environment and corrosion duration.
- Step 3. Calculate the remaining cross-sectional properties.
- Step 4. Calculate the remaining stiffness of the cross-section.
- Step 5. Calculate the maximum deflection of the beam considering time-dependent metal corrosion.

Following the sequence of the steps, the study proceeded to build a flowchart for calculating the maximum steel beam deflection considering metal corrosion, as illustrated in Figure 4. A program was then developed in MATLAB based on the specific flowchart, aiming to investigate the maximum deflection of the steel beams in various environments.

B. *Number Practice*

A steel beam with a geometrical structure and cross-section is shown in Figure 5, and its structural parameters are presented in Table II. A sudden constant force $P = 5000$ N is applied; the ratio of the sudden constant force and the free oscillation frequency $(\frac{t_1}{T})$ is set to 0.2

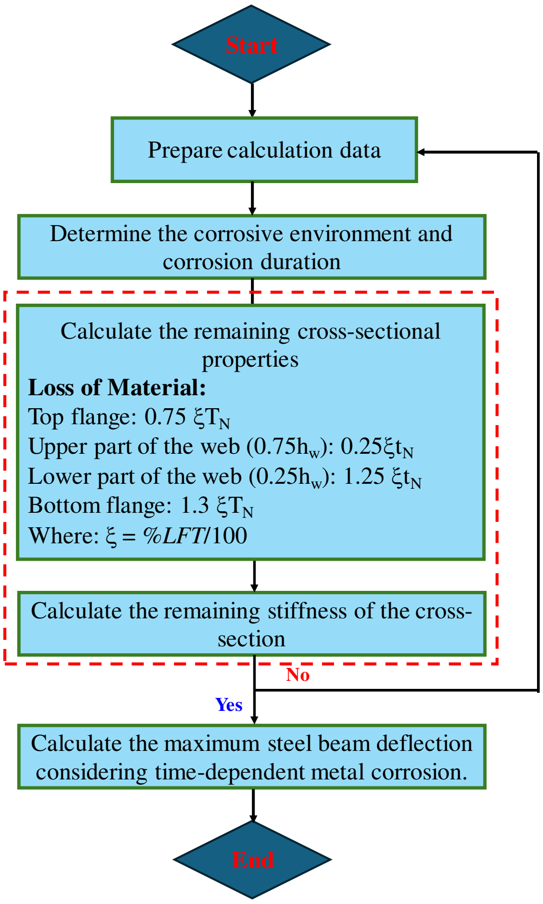

Fig. 4. Flowchart for calculating the maximum deflection of steel beams considering metal corrosion.

TABLE II. GEOMETRICAL STRUCTURE AND CROSS-SECTION

Property	Symbol	Units	Values
Beam span	L	mm	10000
Cross-sectio	b_{f1}	mm	150
	b_{f2}	mm	200
	t_{f1}	mm	10
	t_{f2}	mm	10
	t_w	mm	8
	h_w	mm	300
Material	ρ	kg/m^3	7850
	E	Pa	2.1E+11

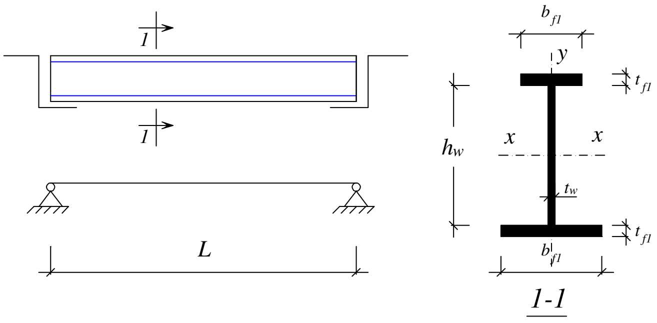

Fig. 5. Diagram of geometrical structure and cross-section.

Figure 6 portrays the results of the maximum steel beam deflection subjected to sudden constant force in a short duration in a rural environment after 100 years. It is observed that the effect of metal corrosion on the maximum steel beam deflection subjected to sudden constant force in a short duration has increased by 6.63%. Although a low corrosion level is observed in the rural environment, the increase in deflection over time remains significant. This emphasizes the importance of considering long-term corrosion factors to ensure the safety and durability of steel structures.

Figure 7 shows the results of the maximum deflection of I-section steel beams subjected to sudden constant force in a short duration in an urban environment after 100 years. It can be observed that the effect of metal corrosion on the maximum steel beam deflection has increased by 12.95%, reflecting the higher corrosion rate in urban environments. Despite the lower corrosion rate compared to marine environments, the increase in maximum deflection over time in the urban setting is still considerable. This highlights the importance of accounting for long-term corrosion effects to ensure the safety and durability of steel structures.

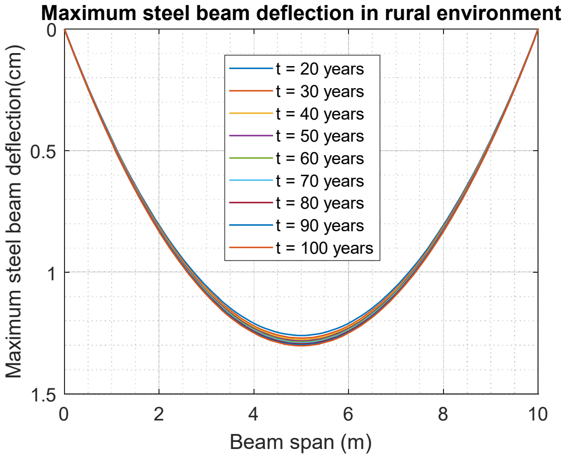

Fig. 6. Diagram of time-dependent maximum steel beam deflection in the rural environment.

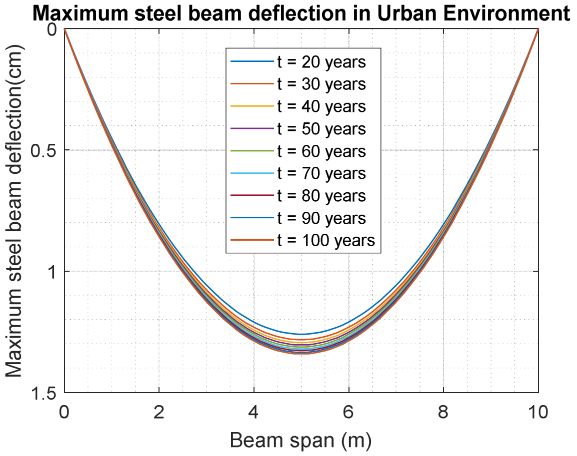

Fig. 7. Diagram of time-dependent maximum steel beam deflection in the Urban Environment.

Figure 8 depicts the results of the maximum deflection of steel beams subjected to sudden constant force in a short duration in a marine environment after 100 years. It can be noted that the effect of metal corrosion on the maximum steel beam deflection has increased by 29.52%, due to the significantly higher corrosion rate in marine environments. The rapid deterioration caused by salt and moisture leads to a substantial increase in the maximum deflection over time. This underscores the critical importance of considering long-term corrosion effects in marine environments to ensure the safety and durability of steel structures.

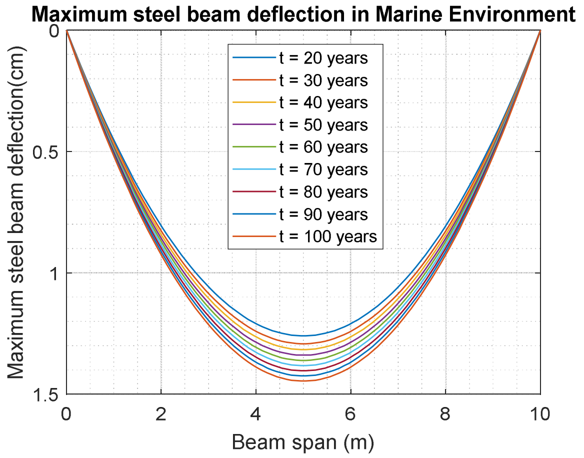

Fig. 8. Diagram of time-dependent maximum steel beam deflection in the marine environment.

The effect of metal corrosion on the maximum steel beam deflection under a sudden constant force over a short duration is the smallest in rural environments and the most significant in marine environments. This can be attributed to the varying levels of corrosive agents being present in these environments. Moreover, the quantitative analysis provides designers and engineers with valuable data, enabling them to adjust structural parameters during the design phase to better account for the corrosion effects. Appropriate protective measures, such as corrosion-resistant materials or coatings, can be implemented by understanding how different environments affect steel beam deflection. Additionally, maintenance schedules can be optimized based on the projected degradation rate, ensuring the structure's longevity and safety.

IV. CONCLUSIONS

This study investigated the effects of metal corrosion on the maximum deflection of I-section steel beams subjected to a sudden constant force in a short duration. Three environmental conditions, namely rural, urban, and marine areas, were considered in the calculation procedure. The following conclusions were obtained.

- A procedure for calculating the maximum deflection of corroded I-section steel beams is proposed. The corrosion model is incorporated, accounting for the reduction of the cross-sectional properties and stiffness.
- Numerical investigations show that in marine environments, the maximum deflection of the steel beams is increased by 29.52% after 100 years, which is significantly higher than that in rural and urban environments.
- It is necessary to incorporate the long-term corrosion impacts in steel structure designs for corrosive environments.

It should be noted that the corrosion model adopted in this study did not consider random corrosive phenomena. Thus, a follow-up study is required to investigate the effect of natural corrosion on steel structures.

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