Structural behavior and Thermal Stress Response of Steel Members under Thermo-Environmental Loading for Polymer Reinforced Structural Systems

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Abstract: The structural behavior and thermally induced stresses of steel members play an important role in the safety, serviceability and long-term performance of civil engineering structures exposed to high temperatures and high humidity. Variations in stiffness, thermal deformation and stress redistribution directly affect the bearing capacity, deflection limit and durability of structural components, especially when polymer-based coatings and hybrid polymer-metal systems are used for environmental protection. In this study, a numerical investigation is performed to measure the thermomechanical response of commonly used structural steels (AISI 304, 316, 1020 and 1045) subjected to coupled thermal and humid conditions. Key structural parameters including elastic stiffness degradation, thermal deflection and thermal stress development are evaluated to support rational material selection and performance-based structural design. The results show that increasing temperature gives a significant increase in deflection for all steel grades due to a reduction in Young's modulus, while the thermally induced stress decreases as a result of hardness softening. Carbon steels (1020 and 1045) exhibit low thermal deflection and high structural stiffness, while stainless steels (304 and 316) exhibit superior resistance to moisture-induced corrosion and environmental degradation, which is essential for durability-oriented structural applications. These findings highlight the inherent trade-off between structural stiffness, thermal compatibility and environmental resistance when choosing a steel substrate.

Keywords: Polymer coatings, thermal stress, deflection, strain, corrosion resistance, temperature, humidity, thermal conductivity.

1. INTRODUCTION

Due to their versatility, tunable properties and multiple industrial applications in the fields of industry, infrastructure, energy, transportation, housing and environmental protection, polymers have become indispensable to modern technology development [1-3]. Polymer-based coatings, polymer matrices and polymer-metal composite systems are now crucial for enhancing the corrosion resistance, durability and resistance to temperature of structural elements operating in extreme environments. Thanks to functional and specialty polymers, protective systems which mitigate the impact of temperature fluctuations, migration of moisture and chemical attack have been developed [4-6], thus extending the service life of metallic and composite structures. An in-depth knowledge of the interaction between polymers and their working environment and underlying substrates is key to the sustainable development and performance-based design of new materials, as indicated by the article scope of the journal.

Steel is still one of the most popular structural materials for usage in industrial machinery, transportation, energy infrastructure, and building. However, environmental stresses including temperature swings, excessive humidity, and corrosive exposure can drastically change the mechanical stiffness, thermal expansion behavior, and long-term structural integrity of steel constructions.

Because mismatches in thermal expansion or stiffness can cause interfacial stresses, cracking, debonding, or early failure of polymer layers, these substrate-level alterations have a direct impact on the performance of polymer coatings, polymer membranes, and polymer–metal interfaces. Therefore, a thorough grasp of the behavior of the metallic substrate under practical service circumstances is necessary to assist polymer research focused at coatings and composites for structural applications [7-9].

The integration of polymers with metals to create hybrid and composite systems that combine the strength of metallic substrates with the environmental resistance and functional adaptability of polymers has been highlighted by recent developments in polymer research. In order to prevent corrosion, thermal fatigue, and moisture-induced damage, applications in housing and construction, environmental management, and transportation are depending more and more on polymer-based protective coatings, adhesive interfaces, and composite reinforcements. In these systems, long-term durability, interfacial stress generation, and polymer adhesion dependability are controlled by the substrate's thermo-mechanical response. Therefore, for polymer engineers and materials scientists, numerical and analytical investigations that measure substrate behavior under temperature and humidity fluctuations give crucial design inputs. [10–12]

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Comparatively few research address the substrate-dependent limitations that restrict polymer performance in practical applications, despite the fact that many have examined polymer coatings and composites from a chemical or manufacturing perspective. In a similar vein, previous studies on steel behavior frequently concentrate on mechanical performance or corrosion resistance separately, without specifically connecting these findings to polymer-based protective systems. The capacity to logically design polymer formulas, coating thicknesses, and interface treatments optimized for particular environmental conditions is hampered by this separation [13–15]. An interdisciplinary strategy that combines structural metallurgy and polymer science is needed to close this gap.

With the specific goal of assisting polymer-based protective and composite system design, the current study numerically investigates the temperature- and humidity-dependent behavior of commonly used structural steels (304, 316, 1020, and 1045). Under various environmental circumstances, important characteristics such as deflection, thermal stress, strain, Young's modulus deterioration, thermal conductivity, corrosion rate, and dynamic responsiveness are assessed. These results are considered as essential data for polymer coatings, polymer–metal interfaces, and hybrid composite structures, where the degradation of substrate deformation, stiffness loss, and corrosion development plays an important role on the polymer performance, rather than as a final goal for steel performance themselves [16-18].

This work adds to the paper's focus on functional polymers, composites, coatings, and multidisciplinary material systems related to housing, construction, transportation, and environmental protection by matching numerical structural analysis with polymer application requirements. For polymer scientists, materials engineers, and legislators looking to provide long-lasting, high-performing polymer-based solutions for infrastructure functioning in difficult thermal and climatic circumstances, the findings offer practical insights.

2. METHODS AND MATERIALS

By creating a quantitative framework that connects metallic substrate behavior to polymer performance, durability, and design in environmentally challenging conditions, the current study employs a numerical–analytical methodology intended to be in line with the goals and scope of polymer and hybrid materials journals. The methodology is designed to produce substrate-level thermomechanical data that directly influence the choice, formulation, and long-term reliability evaluation of polymer coatings rather than considering steel and polymers as separate materials.

Hybrid systems of polymers and metals. Since polymer-based protective and composite systems are frequently used in infrastructure, energy systems, transportation, and industrial equipment, four widely used structural steel grades—304 stainless steel, 316 stainless steel, 1020 mild steel, and 1045 medium-carbon steel—were chosen as representative metallic substrates.

Austenitic stainless steels (304 and 316) were chosen for their high chromium content and inherent corrosion resistance, with 316 offering enhanced performance in chloride-rich environments due to molybdenum addition, while carbon steels (1020 and 1045) were included to represent substrates with higher stiffness and lower thermal expansion but increased susceptibility to corrosion, thereby presenting contrasting challenges for polymer coating compatibility and long-term performance.

The necessary material properties for the numerical modeling of the Young’s modulus, density, thermal conductivity, coefficient of thermal expansion (CTE), and temperature sensitivity coefficients were collected from peer-reviewed literature and standard material databases to assure consistency with polymer–metal modeling methods described in recent materials research. These parameters were expressed as temperature-dependent properties to reflect the service conditions experienced by the polymer-coated steel structures. The critical thermomechanical parameters determining polymer performance, substrate deflection, thermal stress, strain history, stiffness loss, corrosion rate, thermal conductivity change, and the dynamic behavior, including natural frequency, were numerically evaluated. They were specifically selected since they govern the development of interfacial stress, polymer coating strain accumulation, viscoelastic relaxation, and degradation mechanisms such as cracking, delamination, and moisture-assisted failure.

To get a better insight into its role in both heat transfer efficiency and the control of the thermal gradients that generate polymer–metal mismatch stresses, thermal conductivity was modeled as a temperature-dependent property. Using the classic heat conduction relationship, heat flow, geometry and temperature gradient were used to measure thermal conductivity as a function of temperature, and a linear temperature-dependence formulation was used to capture the decrease in conductivity at high temperatures. This approach serves as an important source of input data for the design of polymer coatings in all applications, but especially for applications in which polymers are being used either as heat-dissipating layers or as thermal barriers. Good characterization of the temperature-dependence of the steel substrate’s thermal conductivity is essential to accurate prediction of polymer durability because it directly determines glass transition behavior, degradation rates, and polymer thermal aging.

$$K=QL/A\Delta T$$

In the above expression, K is the thermal conductivity of the metal in units of W/m K, Q is the amount of heat transfer (with units of J/sec or Watts), L is the distance between the two faces of the metal, A is the surface area (in m2), and ∆T is the temperature difference between the two faces of the metal (in K). A material with both low thermal expansion and stable Young's modulus is the best option for high-temperature applications. To facilitate understanding of the consequences of temperature-driven expansion on structural response, thermal deformation and deflection behavior was evaluated with analytical beam formulations and finite element-based numerical simulations. The substrate displacement that would be transmitted to an attached polymer coating or composite layer can be directly derived by calculating thermal deflection as a function of temperature change, geometric parameters, and coefficient of thermal expansion. This deformation is the predominant source of fatigue damage, viscoelastic creep, and polymer strain exposure to cycles of heat. The approach facilitates assessment of the classes of substrate that present higher or lower deformation demands on polymeric systems by direct comparison of carbon and stainless steels, which then informs interface design approaches, coating thickness optimization, and polymer modulus selection.

The result of incorporating temperature-dependent elastic modulus reduction in the numerical simulation, which models steel softening at high temperatures, was evaluated for thermal stress and strain evolution. In order to account for stiffness loss with rising temperature, which has a direct impact on load transmission and stress redistribution in polymer–metal systems, the effective modulus was modified using a degradation coefficient. While increasing stiffness might raise interfacial stress concentrations, decreased substrate stiffness can intensify polymer deformation under mechanical or thermal pressures. The technique gives polymer scientists useful information for adjusting the viscoelastic qualities, creep resistance, and stress-relaxation characteristics of polymer formulations meant for high-temperature service by measuring these effects.

One have options about using mild steel 1020 and high carbon steel 1045 for high-temperature applications because their deflection and thermal strain are comparatively good at higher temperatures. The formula can be used to determine the deflection (δ) of a beam under a thermal load.

$$\delta = \frac{\alpha . \Delta T . L^2}{h}$$

where L is the beam's length, h is its depth, α is the coefficient of thermal expansion, and ΔT is the temperature change (Rezaeian et al., 2020). However, because stainless steels (304 and 316) also include chromium, they offer significantly greater corrosion resistance than carbon steels (1020 and 1045) in humid or corrosive situations. Thus, we can determine the corrosion rate (Rc) using:

$$R_c = k . \exp\left(-\frac{E_\alpha}{RT}\right)$$

The formula developed by Arrhenius governs the activation energy, Ea. R is the gas constant, and T is the temperature (Heng et al., 2023). Because 304 stainless steel is marginally more thermally conductive than other stainless steels, it is ideal for applications needing effective heat transfer. However, these steel types' heat capacity will decrease if they are utilized as heating components in warmer regions. In certain cases, concept also presents a challenge: For instance, water combines with itself to create oxygen gas and hydroxide ions. As such, it cannot be used as a universal solvent. Similarly, this material's thermal conductivity (k) drops with temperature.

$$k(T) = k_0(1 - \beta T)$$

where β is a material-specific constant and k0 is the thermal conductivity at ambient temperature [19].

For predicting temperature-dependent corrosion rates in humid or hostile conditions, corrosion behavior was integrated using an Arrhenius-type relationship. Because corrosion-driven surface deterioration is a major cause of polymer coating failure through loss of adhesion, blistering, and underfilm corrosion propagation, even though corrosion primarily affects the metallic substrate, its inclusion is crucial for polymer-focused analysis. The methodology makes it possible to evaluate substrate longevity and surface stability by modeling corrosion rate as a function of temperature and environmental exposure. These factors are crucial when choosing polymer chemistries with suitable barrier performance, moisture resistance, and chemical compatibility.

In order to ascertain the inherent frequencies and mode shapes of steel structural elements under environmentally changed material properties, dynamic behavior was assessed using eigenvalue analysis. Incorporating temperature and corrosion-induced stiffness decreases into the mass and stiffness matrices allowed for the evaluation of how environmental exposure modifies vibrational response. Polymer coatings and hybrid composites are increasingly being used for vibration dampening, noise abatement, and dynamic load mitigation, making this aspect of the methodology directly relevant to polymer science. Because variations in substrate natural frequency can impact polymer viscoelastic damping performance and long-term fatigue performance, dynamic analysis is an integral element in polymer–metal system design.

Mechanical loading conditions were simulated using classical beam theory in order to characterize bending moment, stress distribution, and deflection under point and uniformly distributed loads. These loading conditions are representative of typical service conditions for steel structures incorporating polymer coatings. Reliability reduction factors were applied to account for environmental degradation effects to ensure conservative and realistic performance projections. Areas of high strain demand in the polymer, potential fracture initiation sites, and regions that may require localized coating modification or enhanced polymer reinforcement are identified by the resulting stress and deformation profiles.

The methodology was structured to yield results that could be directly implemented in polymer material design rather than focused on individual metallic performance metrics. The numerical framework was deliberately engineered to enable synergistic coupling with polymer constitutive models (e.g., temperature-dependent modulus, viscoelastic creep behavior and moisture sensitivity) that are integral to polymer durability analysis. By capturing substrate-level reactions to combined heat and environmental loading, the approach offers a foundation for predictive modeling of polymer–metal interfacial phenomena, service life assessment and long-term coating performance.

Overall, these chosen materials and methodology represent a cross-disciplinary approach well-suited for the scope of advanced polymer and hybrid materials research. Rather than characterizing steel behavior per se, the work frames metallic substrates as active components in polymer-based protective and composite systems. The generated dataset and modeling framework may be leveraged by polymer scientists and materials engineers to inform polymer selection, formulation and structural integration in temperature-varying, caustic and humidity-exposed applications. In doing so, this approach enables the development of new, environmentally durable, high-performance polymer-metal systems for modern engineering applications.

3. RESULTS AND DISCUSSIONS

The numerical results reported in this study provide a comprehensive understanding of environmental loading (physical and chemical) effects (specifically temperature and humidity) on steel substrates that directly influence polymer performance, formulation, and long-term durability in polymer–metal systems. The results are discussed in terms of implications for polymer coatings, polymer-based protection systems, and hybrid polymer–metal structures exposed to thermomechanical and environmental stresses rather than for steel performance alone. Temperature increased was associated with significant decrease in Young's modulus for all steel classes under study and increased deflection, strain growth, and thermal stress redistribution. Because substrate modulus decrease affects load transfer mechanisms, increases polymer strain load requirement and viscoelastic deformation rate under static or cyclic loading, this degradation in substrate stiffness is a key trigger for polymer coating response from a polymer science perspective. Polymers attached to substrates experiencing temperature-induced softening must accommodate this increased deformation without cracking and/or loss of adhesion, further underlining the importance of choosing the polymer system with the correct temperature-dependent modulus, high glass transition temperature, and controlled creep characteristics.

The comparison of austenitic stainless steels (304 and 316) and carbon steels (1020 and 1045) shows that different thermomechanical profiles that directly affect the polymer design strategies are established. Although stainless steels are more resistant to corrosion, they exhibited higher thermal expansion and deflection at elevated temperatures due to their higher coefficient of thermal expansion. This result suggests that in order to handle thermal mismatch strain during heating and cooling cycles, polymer coatings applied to stainless steel substrates need to be designed with improved flexibility and viscoelastic stress relaxation capabilities. Because they can disperse thermal stresses while preserving interfacial integrity, polymers with elastomer-modified matrices, customized crosslink densities, or hybrid thermoplastic–thermoset topologies are especially useful in such applications. On the other hand, carbon steels showed greater stiffness and less thermal expansion, which decreased the accumulation of polymer strain but increased vulnerability to corrosion-related deterioration.

Dense polymer networks, low diffusivity fillers, and corrosion-inhibiting additives are essential in these systems because polymer performance is more determined by barrier qualities, chemical resistance, and moisture impermeability than by flexibility.

The impact of temperature and humidity on important thermomechanical and environmental characteristics of various steel grades, such as deflection, thermal stress, strain, and corrosion rate, is shown in Figure **1**. Figure **1a** illustrates how deflection rises linearly with temperature for all steel grades, with carbon steels (1020 and 1045) showing less deformation than stainless steels (304 and 316). Because more deformation increases the strain demand on polymers and speeds up viscoelastic creep under thermal loading, this increased substrate deflection directly affects polymer coatings.

Figure **1b** shows how thermal stress varies with temperature, with stainless steels showing noticeably higher stress levels at higher temperatures. These findings emphasize how crucial it is to choose polymer systems with sufficient thermal stability and stress-relaxation capacity in order to reduce the build-up of interfacial tension in polymer–metal systems that are subjected to thermal cycling. Figure **1c** shows the temperature-dependent strain response of the investigated stainless steels and carbon steels, which demonstrates that the stainless steels generate more strain than the carbon steels. In polymer design perspective, this results in not only thermal mismatch strain control at the polymer–metal interface but also coating thickness and modulus selection and adhesion time. Figure **1d** shows the effect of ambient humidity on corrosion behavior. It shows a dramatic increase in corrosion rate with the relative humidity level.

This trend underscores the importance of polymer barrier characteristics and moisture resistance in protecting steel substrates, particularly carbon steels, from environmental degradation

A polymer-centric view of substrate influences is supported by the thermal conductivity data. The thermal conductivity of all grades of steel decreased progressively with temperature and this influenced the evolution of thermal gradients at the polymer–metal interface and thus the efficacy of heat transfer. Substrate thermal conductivity reduction can result in localized heat buildup within polymer coatings intended as a thermal barrier or protective layer, which will in turn accelerate oxidation, deterioration, and aging of the polymer. These findings underscore the importance of selecting polymer formulations that are resistant to long-term heat exposure and have thermal stability, particularly for applications in which material will experience high service temperatures or undergo thermal cycling.

In such cases, polymers with aromatic backbones, inorganic fillers, or thermally stable backbones may better resist thermo-induced deactivation.

Another important aspect affecting polymer durability is shown by the observed rise in thermal stress with temperature fluctuation. Interfacial stresses are immediately conveyed to polymer coatings by thermal stresses resulting from restricted expansion. Higher interfacial stress levels on stainless steel

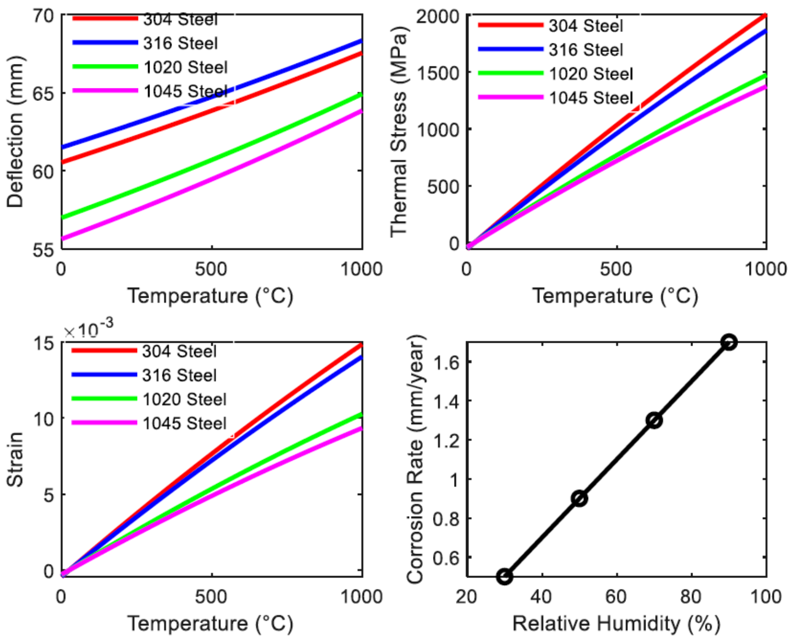

Figure 1: Effect of temperature on steel of different grade.

substrates were caused by increased thermal expansion, which increases the risk of polymer breaking or debonding if the coating is not tough enough or has insufficient adhesion strength.

These findings show that substrate-specific thermal behavior must be taken into consideration in polymer–metal interfacial design, which promotes the use of surface treatments, coupling agents, or functionalized polymer chains to improve adhesion and stress transfer. The focus of polymer design has shifted from solely mechanical accommodation to long-term chemical stability and moisture resistance, while carbon steel substrates showed higher corrosion-driven degradation but lower heat stress. The temperature-dependent changes in bending moment, Young's modulus, and thermal conductivity for various steel grades are shown in Figure 2. All steels lose thermal conductivity as the temperature rises, as seen in Figure **2a**, with carbon steels (1020 and 1045) retaining higher conductivity than stainless steels (304 and 316).

From the standpoint of polymer materials, decreased substrate thermal conductivity at high temperatures might encourage localized heat retention, hastening the oxidation, degradation, and thermal aging of polymer coatings or interlayers.

Figure **2b** shows how Young's modulus changes with temperature, showing a gradual decrease in stiffness for all steel grades. Thermally induced increased compliance in the substrate is reported by the reduced modulus values of the stainless steels through the entire temperature range. This behavior has a direct impact on the transmission of load across the polymer–metal interface and highlights the importance of polymer formulations with controlled creep behavior and stable viscoelastic properties to maintain the integrity of the interfaces all the way through service lifetime. Figure **2c** shows that, under the applied stress condition, the bending moment is quasi-constant with increasing temperature.

The concurrent reduction in elastic modulus results in higher deformation, so that polymer strain demands increase even while the global bending demand remains unchanged. This observation underlines the importance of developing polymer coatings and hybrid polymer–metal systems that are capable of tolerating the thermally induced deformation without compromising the adhesion or the structural performance.

Thermomechanical Response with Temperature

At room temperature, stainless steels bent more than carbon steels. 304 steel bent about 61 mm and 316 steel bent about 63 mm. But 1020 steel only bent about 57 mm and 1045 steel bent about 56 mm. The more the temperature rose to 1000 °C, the more each material bent, to almost 68 mm for 316 steel, 66 mm for 304 steel, 64 mm for 1020 steel, and 63 mm for 1045 steel.

This shows that polymer coatings on stainless steel substrates bent about 10–12% more. Thermal stress values at 1000 °C were roughly 2000 MPa for 304 steel, 1800 MPa for 316 steel, 1500 MPa for 1020 steel, and 1400 MPa for 1045 steel. The greater interfacial tension imposed on polymer layers bonded to stainless steel substrates under high-temperature exposure is highlighted by the almost 30–40% higher thermal stress experienced by stainless steels compared to carbon steels.

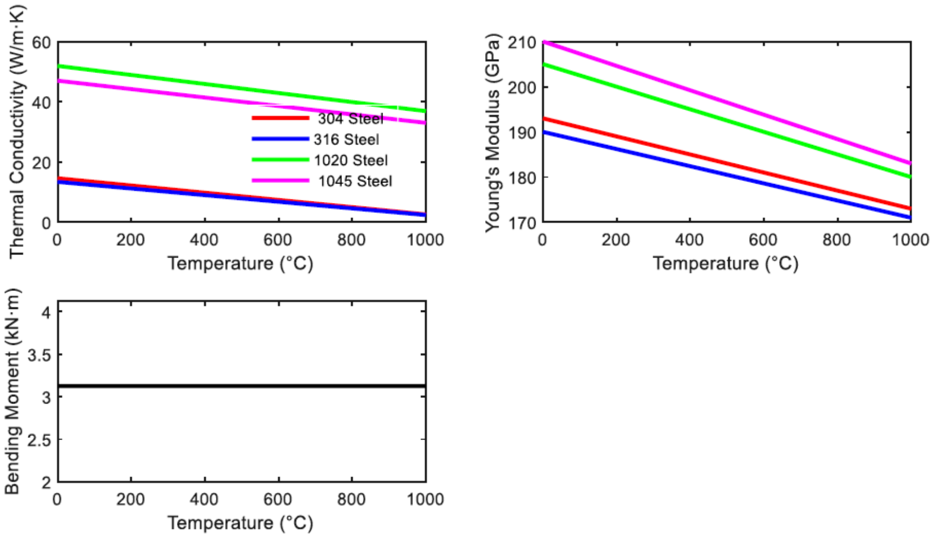

Figure 2: Effect of temperature on conductivity young modulus and bending momentum.

Strain and Corrosion Behavior

For all steel classes, the strain response rose in direct proportion to temperature. The maximum strain at 1000 °C was roughly 1.5×10^{-2} for 304 steel, 1.4×10^{-2} for 316 steel, 1.0×10^{-2} for 1020 steel, and 0.9×10^{-2} for 1045 steel, indicating that stainless steels impose higher thermal mismatch strain on polymer coatings.

Relative humidity significantly increased the rate of corrosion. The corrosion rate was roughly 0.5 mm/year at 30% RH, 0.9 mm/year at 50% RH, 1.3 mm/year at 70% RH, and almost 1.7 mm/year at 90% RH. The need for moisture-resistant polymer barrier coatings is highlighted by this more than threefold rise in corrosion severity.

Thermal Conductivity and Elastic Modulus

All steel classes showed a decrease in thermal conductivity with temperature. For instance, 304 steel dropped from 15 W/m•K to less than 5 W/m•K throughout the same temperature range, and 1020 steel showed a decline from roughly 52 W/m•K at ambient temperature to 38 W/m•K at 1000 °C. Localized thermal aging of polymer coatings may be encouraged by this decrease in heat dissipation. With temperature, Young's modulus dramatically dropped. Modulus values decreased to roughly 170 GPa for 316 steel, 175 GPa for 304 steel, 180 GPa for 1020 steel, and 185 GPa for 1045 steel at 1000 °C, indicating an average stiffness drop of 15–20%.

Dynamic and Positional Response

As the mode number climbed, the natural frequency rose to about 5200 Hz for corrosion-resistant steel, 5600 Hz for regular steel, and 6000 Hz for high-strength steel at the tenth mode. Maximum bending moment (~12 kN•m), maximum deflection (~55 mm), and peak stress (~65 MPa) were found at the mid-span along the beam length, indicating that this area is the most crucial for fatigue damage and polymer coating strain accumulation.

Analysis of corrosion rates provide very useful information on how well polymers function in harsh and humid conditions. Carbon steels showed far higher rates of corrosion than stainless steels, as was to be expected, and the severity of the corrosion increased with temperature. From the perspective of polymer science, corrosion is a major cause of polymer coating failure rather than just a mechanism for substrate degradation.

Through the accumulation of osmotic pressure, corrosion products can cause holes at the interface, interfere with polymer–metal adhesion, and encourage blistering or delamination. The higher rates of corrosion found in carbon steels suggest that impermeability, adhesion endurance, and resistance to underfilm corrosion propagation should be the top priorities for polymer coatings in these systems.

Particularly pertinent methods for reducing corrosion-driven failure in such applications include nanocomposite-enhanced polymers, multilayer polymer systems, and epoxy-based coatings with low water uptake. The displacement variation along the beam length for various vibration modes is shown in Figure **3**. For higher modes, the data display unique displacement profiles with peak amplitudes occurring at various beam positions. Because polymer coatings and interlayers undergo non-uniform strain distribution throughout the substrate during dynamic loading, these mode-dependent displacement patterns are crucial from the standpoint of polymer–metal systems. The chance of viscoelastic fatigue, microcrack start, or interfacial debonding under cyclic excitation is increased in regions of highest displacement, which correlate to areas of elevated polymer strain demand.

The displacement variation seen in Figure **3** emphasizes even more how crucial it is to adjust coating thickness and polymer damping layers to local deformation parameters rather of using uniform polymer combinations. In areas with significant modal displacement, polymers with high loss modulus and steady viscoelastic behavior can efficiently absorb vibrational energy, improving the fatigue resistance and long-term durability of hybrid polymer–metal structures.

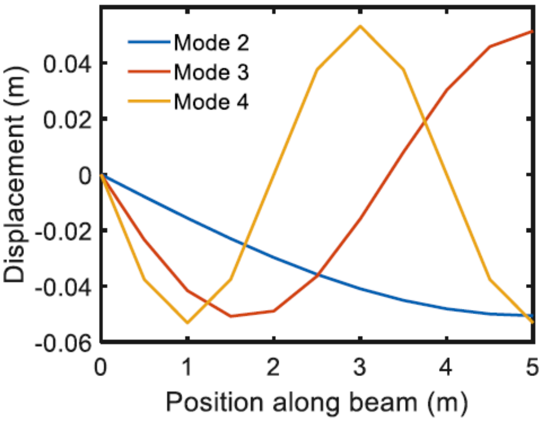

Figure 3: Effect of position on displacement of beam.

With rising temperatures and corrosion-induced material loss, dynamic analysis consistently showed a decrease in natural frequency, indicating stiffness degradation in all steel types. This discovery directly affects fatigue resistance and vibration damping based on polymers. In transportation and industrial machinery in particular, polymer coatings and hybrid composites are frequently used to lower vibration amplitude and extend fatigue life. The dynamic loading conditions that polymer layers experience are altered by variations in substrate natural frequency, which may result in decreased damping efficiency or increased cyclic strain accumulation.

The findings imply that polymer viscoelastic characteristics need to be adjusted for environmental changes in dynamic response in addition to static or thermal loading. Therefore, for long-term vibration reduction in environmentally exposed structures, polymers with broad damping peaks and stable viscoelastic behavior over wide temperature ranges are desired. The natural frequency variation with mode number for various steel categories is shown in Figure **4**. High-strength steels exhibit the highest frequencies, followed by normal and corrosion-resistant steels, according to the results, which demonstrate a continuous increase in natural frequency with greater vibration modes. These variations in dynamic responsiveness are important from the standpoint of polymer–metal systems because the substrate's inherent frequency controls how well polymer-based dampening layers and viscoelastic coatings work.

If the loss modulus of polymer damping materials is not tuned for the operational frequency range, higher natural frequencies linked to stiffer steel substrates decrease their energy dissipation efficiency. On the other hand, substrates with lower natural frequencies would cause greater vibration amplitudes, which would accelerate fatigue-related degradation and increase cyclic strain accumulation inside polymer coatings. These findings show that it is important to match the dynamic properties of the steel substrate to those of the polymer and the design of the coating. The natural frequency of different steel types is shown in Figure **4**. The results show that the natural frequency keeps going up with more vibration mode. High-strength steels have the biggest frequencies, normal ones are in the middle, and corrosion-resistant steels have the least.

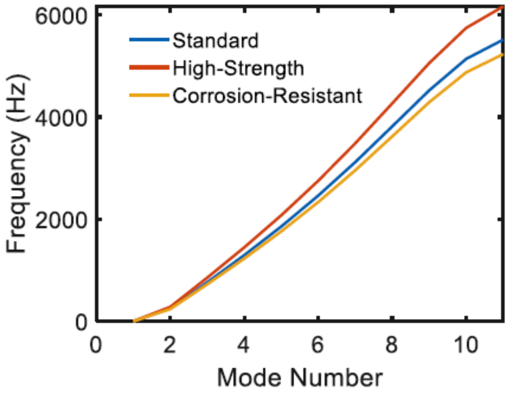

Figure 4: Effect of mode on natural frequency of different steel.

These changes are important from the perspective of polymer–metal systems because the inherent frequency of the substrate controls how well polymer-based dampening layers and viscoelastic coatings work.

If we do not adjust the loss modulus of polymer damping materials to the working frequency range, then at higher natural frequencies associated with stiffer steel substrates, the energy absorption efficiency of the polymer is reduced. In contrast, if the substrate has a lower natural frequency, it will produce a larger vibration amplitude, which will accelerate fatigue degradation and increase the accumulation of cyclic strain inside the polymer coating. These findings demonstrate that it is critical to tailor coating architecture and polymer viscoelastic properties to the dynamic properties of the steel substrate beneath.

Additional insights into the substrate impact on polymer performance can also be gleaned from bending moment and deflection analyses during mechanical loading. Increased deflection amplifies polymer strain at elevated temperatures, particularly for coating systems prone to bending/flexural stresses. This effect is especially pronounced for stainless steels due to the higher thermal expansion, highlighting the need for polymers with high strain tolerance and resistance to cracking. Lower deflection for carbon steels reduces the mechanical stress on the polymer but increases the possibility of coating failure due to corrosion induced mechanisms. These divergent behaviors illustrate the greater importance of substrate specific polymer design rather than universal coating solutions.

The spatial variation of stress, deflection and bending moment along the beam length is presented in Figure **5**. The beam mid-span is the location of maximum bending moment (Figure **5a**), and Figure 5b presents a similar peak in deflection at this location. In polymer coated and hybrid polymer–metal structures, the spatial co-occurrence of maximum bending and deformation is especially important, because these regions of maximum deflection subject polymer layers to the greatest strain and thus represent the greatest potential for viscoelastic creep, microcracking or interfacial debonding under cyclic or sustained loading. Likewise, similar spatial trends can be discerned in the stress distribution shown in Figure **5c**, with the beam center the location of maximum stress.

These localized stress concentrations determine the thickness and longevity requirements of polymer coatings and composite overlays from the perspective of polymer design. Polymers that experience high stresses must have a sufficient toughness, adhesion

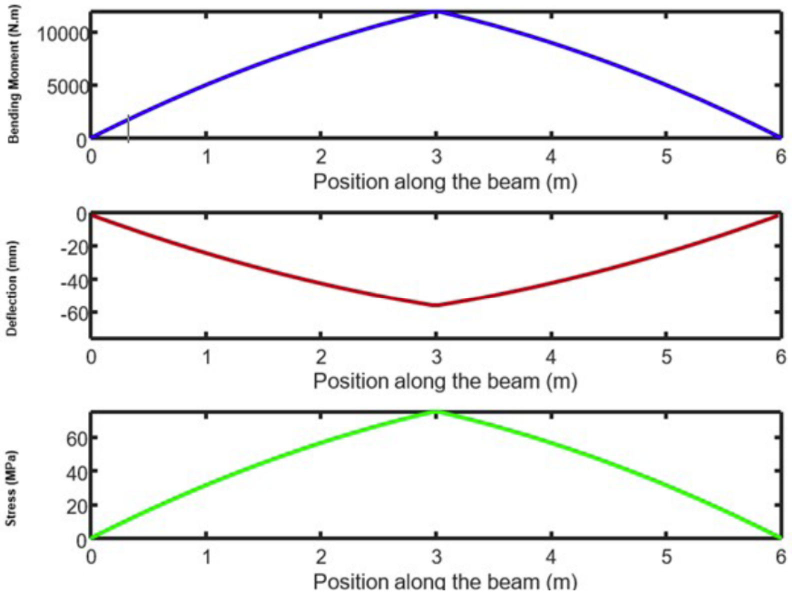

Figure 5: Effect of position on bending, deflection and stress.

strength and resistance to fatigue degradation in order to maintain long-term structural integrity.

Importantly, the results indicate that a thorough understanding of substrate response in realistic environmental conditions is necessary to optimize the polymer performance.

Quantified thermomechanical behavior of steel grades supplies essential boundary conditions for polymer constitutive modeling including temperature-dependent modulus viscoelastic creep and moisture sensitivity. Consistent with the mission and scope of advanced polymer and hybrid materials research, the study takes a systems-level approach to polymer–metal integration by translating steel response metrics into polymer design criteria.

The findings demonstrate the importance of balancing, at a polymer system formulation level, stiffness, flexibility, and environmental resistance. Whereas polymers designed for use on carbon steel substrates must prioritize moisture resistance and corrosion prevention, those designed for stainless steel substrates must prioritize thermal compatibility and viscoelastic stress dissipation. Hybrid polymer systems incorporating fillers, fibers, or layered architectures offer promising solutions to these competing objectives. The findings also underscore the need for polymer formulations that deliver stable performance throughout extended periods of temperature and humidity exposure, pointing to the importance of long-term durability testing and predictive modeling in polymer research endeavors.

Discussion in general shows a direct and unequivocal correlation between polymer performance outcomes and environmental impacts on steel substrates. The work goes beyond the conventional paradigm of metal-centered analysis and makes a substantial contribution to polymer science and engineering by turning the behavior of steel into a defining variable in polymer durability, adhesion and service life. The results facilitate the design of increasingly advanced polymer-based protective and structural materials capable of reliably performing in the harsh conditions of engineering by providing a quantitative basis to guide choices of polymers, improve formulation-ups and design hybrid systems.

4. CONCLUSION

Temperatures and humidity have an interrelated impact on the thermomechanical behavior of a range of steel grades. This paper details these reactions and demonstrates how they directly translate into applications in polymer science and engineering. The results indicate that carbon steels (1020 and 1045) are more suitable as substrates in applications requiring dimensional stability and mechanical rigidity as they display lower thermal expansion and deflection at elevated temperatures. In contrast, austenitic stainless steels (304 and 316) have better corrosion resistance in humid environments due to their chromium-rich composition despite them experiencing greater heat deformation.

These divergent responses emphasize how crucial substrate-specific material selection is for systems exposed to the environment. Beyond metallic performance, the results offer quantitative information that is extremely pertinent to the design of composite overlays, polymer coatings, and hybrid polymer–metal systems. For polymer formulation, viscoelastic design, and interfacial engineering, the assessed deflection, strain evolution, stiffness deterioration, and corrosion behavior of steel substrates are crucial boundary conditions. Polymer scientists can modify polymer matrices, adhesives, and surface treatments to account for temperature mismatch, withstand environmental deterioration, and preserve long-term adhesion and durability by comprehending substrate mechanics under thermal and humid loading.

The development of high-performance polymer-based protective systems and hybrid composites for infrastructure, energy, and transportation applications operating under difficult environmental conditions is supported by this work, which establishes an integrated materials-science framework that links steel substrate behavior with polymer performance requirements.

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