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Structural Redundancy Metrics for Progressive Collapse in High-Rise Frames

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Abstract

Progressive collapse in high-rise structures represents a catastrophic failure mode wherein localized damage propagates disproportionately, leading to partial or total structural failure. As urbanization accelerates the construction of increasingly complex tall buildings, evaluating their resilience against abnormal loads has become paramount. This paper investigates the predictive capacity of structural redundancy metrics in forecasting progressive collapse probabilities using advanced reliability testing frameworks. By synthesizing topological, geometric, and load-path redundancy indicators, this study develops a comprehensive framework to quantify structural robustness without relying on computationally prohibitive nonlinear dynamic simulations for every design iteration. The research employs probabilistic reliability methods, including extensive Monte Carlo simulations, to analyze multi-story steel and reinforced concrete frames under various column-removal scenarios. The findings demonstrate a strong correlation between specific redundancy indices and structural survival rates, suggesting that optimized redundancy metrics can serve as reliable preliminary predictors for collapse resistance. The integration of these metrics into standard design protocols offers a proactive approach to mitigating disproportionate collapse, enhancing occupant safety, and establishing more resilient urban infrastructures.

Keywords: Progressive Collapse; Structural Redundancy; Reliability Testing; High-Rise Frames; Structural Reliability

1. Introduction

The phenomenon of progressive collapse has garnered significant attention in the field of structural engineering over the past several decades. This catastrophic event occurs when a primary load-bearing element fails due to abnormal loading events such as explosions, vehicle impacts, severe fires, or design flaws. The initial localized failure triggers a chain reaction, transferring immense loads to adjacent members that are inadequately designed to absorb such dynamic redistribution. Consequently, these adjacent members fail in succession, culminating in a disproportionate collapse of the structure. The tragic events of the Ronan Point apartment collapse and the World Trade Center disaster underscore the critical need to understand and mitigate this domino effect in structural systems as documented in early investigations [1]. High-rise frames, characterized by their significant vertical loads and complex spatial geometries, are particularly vulnerable to such cascading failures, necessitating rigorous analytical approaches to ensure structural integrity and public safety.

To counter the threat of progressive collapse, modern design philosophies have increasingly emphasized the concept of structural robustness, which is inherently linked to structural redundancy. Redundancy in this context refers to the ability of a structural system to mobilize alternative load paths following the loss of a primary supporting element. While traditional structural design focuses on satisfying ultimate limit states for expected gravity and lateral loads, designing for progressive collapse requires a paradigm shift towards evaluating the system's behavior in a damaged state [2]. Evaluating this behavior involves understanding the intricate interplay between material ductility, connection strength, and the topological arrangement of structural members. Despite its importance, quantifying redundancy in a manner that directly translates to collapse resistance remains a complex challenge. Current design codes often provide prescriptive guidelines, such as the Alternate Path Method, which, while useful, do not explicitly quantify the underlying redundancy or provide a probabilistic measure of structural safety [3].

Reliability testing introduces a probabilistic dimension to structural analysis, acknowledging the inherent uncertainties in material properties, construction quality, and loading conditions. By framing the progressive collapse problem within a reliability engineering context, engineers can assess the probability of failure rather than relying solely on deterministic pass or fail criteria. Reliability analysis utilizes statistical methods to model the variability of input parameters and evaluates the structural response over a vast number of simulated scenarios [4]. This approach is particularly beneficial for high-rise frames, where deterministic analysis may either overestimate structural capacity by ignoring material variability or underestimate it by failing to account for secondary load-resisting mechanisms such as catenary action in beams and floor slabs.

The primary objective of this research is to establish a rigorous methodology for predicting progressive collapse probabilities directly from quantified structural redundancy metrics. By bridging the gap between deterministic topological indicators and probabilistic reliability outcomes, this paper aims to provide structural engineers with robust predictive tools for early-stage design evaluation. The research focuses on developing explicit mathematical definitions for various redundancy metrics, integrating them with probabilistic models of high-rise frames, and validating their predictive accuracy through comprehensive reliability testing. Through this investigation, the paper seeks to contribute to the advancement of resilient structural design, ensuring that future high-rise developments possess the inherent capacity to withstand unforeseen localized damage without succumbing to global failure.

1.1 Scope and Objectives

The scope of this investigation encompasses the analysis of multi-story, multi-bay frame structures, focusing specifically on steel moment-resisting frames and reinforced concrete frames. These structural typologies are prevalent in high-rise construction and offer distinct mechanisms for load redistribution following the loss of a column. The study confines its evaluation to gravity load-driven progressive collapse, utilizing sudden column removal scenarios as the initiating event for damage propagation. The principal objective is to formulate a cohesive suite of structural redundancy metrics that capture both the topological connectivity of the frame and the physical force-distribution capabilities of its members.

Furthermore, the research aims to implement a reliability testing framework capable of processing these metrics against a backdrop of stochastic material and loading variables. A key secondary objective is to evaluate the sensitivity of progressive collapse probabilities to variations in specific structural parameters, such as beam-to-column connection ductility and floor slab diaphragm action. By systematically isolating and testing these variables, the study intends to delineate the hierarchy of redundancy metrics in terms of their influence on overall structural robustness. Ultimately, the goal is to derive empirical correlations that can inform structural design guidelines, enabling a performance-based approach to progressive collapse mitigation that is both scientifically rigorous and practically applicable in the engineering industry.

2. Literature Review and Theoretical Background

The study of progressive collapse and structural redundancy is built upon a foundation of extensive empirical research and theoretical development. Following early structural failures, the engineering community recognized that traditional design methods, which assume an intact load-resisting system, were inadequate for preventing disproportionate collapse. Early research focused heavily on defining the mechanisms of collapse and establishing the criteria for robustness. The concept of structural robustness was initially formalized as a measure of a structure's insensitivity to local damage [5]. This definition paved the way for subsequent studies to explore how structures could be designed to compartmentalize failure, thereby preventing a localized issue from compromising the global stability of the building.

Over the years, various methodologies have been proposed to assess progressive collapse potential. The most widely adopted approach in current engineering practice is the Alternate Path Method. This deterministic technique involves analytically removing a critical load-bearing element, typically a ground floor column, and assessing whether the remaining structure can bridge the resulting gap. While standard guidelines have adopted this method, researchers have continually pointed out its limitations. Specifically, traditional Alternate Path analyses often employ static linear or nonlinear procedures that fail to adequately capture the dynamic amplification effects inherent in sudden structural failures [6]. Consequently, academic literature has increasingly advocated for the use of nonlinear dynamic analysis, which, although computationally expensive, provides a more accurate representation of the inertial forces and energy dissipation mechanisms at play during a collapse event.

2.1 Evolution of Structural Redundancy Metrics

Structural redundancy, while conceptually understood as the provision of alternative load paths, has proven difficult to quantify uniformly. Early attempts to define redundancy relied primarily on the degree of static indeterminacy. However, as numerous researchers have demonstrated, static indeterminacy alone is an insufficient indicator of robustness because it does not account for the spatial distribution of structural members or their individual load-carrying capacities [7]. A highly indeterminate structure may still suffer progressive collapse if its members lack the requisite ductility or if the structural topology funnels redistributed loads into vulnerable elements.

To address these shortcomings, the literature has seen the introduction of more sophisticated redundancy metrics. Topological redundancy metrics, derived from graph theory, have been proposed to evaluate the connectivity and alternative pathways within a structural framework independently of member sizing. These metrics analyze the nodes and edges of a structural model to determine the presence of multiple load transfer routes. Alongside topological approaches, energy-based redundancy metrics have been developed. These indicators assess the structure's capacity to absorb and dissipate the kinetic energy generated during the sudden loss of a support [8]. Energy-based methods emphasize the critical role of material ductility and connection rotation capacity, arguing that true redundancy relies on the ability of structural elements to undergo significant plastic deformation without fracturing.

2.2 Advances in Reliability Engineering for Structural Assessment

Reliability engineering provides the theoretical framework necessary to account for the uncertainties inherent in real-world structural systems. In the context of progressive collapse, uncertainties arise from fluctuations in material yield strengths, variations in live loads, and the unpredictable nature of the initiating extreme event. Traditional structural reliability methods calculate a probability of failure by establishing a limit state function, which defines the boundary between structural survival and failure. Early applications of reliability theory to progressive collapse were limited by the immense computational demands of performing iterative nonlinear analyses within a probabilistic framework [9].

Recent advancements in computational power and statistical sampling techniques have significantly expanded the feasibility of structural reliability testing. The integration of Monte Carlo simulations with advanced finite element modeling has emerged as a robust method for evaluating collapse probabilities. By generating thousands of statistically plausible structural models and subjecting each to column-loss scenarios, researchers can observe the probabilistic distribution of structural responses [10]. Furthermore, the development of surrogate modeling techniques, such as response surface methodologies and artificial neural networks, has enabled researchers to approximate the outcomes of complex finite element analyses. These surrogate models drastically reduce computational time, allowing for more extensive reliability testing and facilitating the exploration of complex correlations between quantifiable redundancy metrics and overall progressive collapse probabilities.

3. Structural Redundancy Metrics Framework

To systematically investigate the relationship between structural design characteristics and progressive collapse resistance, it is imperative to establish a rigorous framework of structural redundancy metrics. This framework must transcend qualitative descriptions of robustness, translating physical and spatial structural properties into quantifiable indices that can be mathematically evaluated. The proposed framework categorizes redundancy metrics into two primary domains. The first domain encompasses topological and geometric indicators, which analyze the spatial arrangement, connectivity, and load-path diversity inherent in the structural grid. The second domain focuses on mechanical and force-distribution metrics, which evaluate the capacity, ductility, and overstrength of the structural components themselves.

By separating redundancy into these distinct domains, the framework acknowledges that structural robustness is a product of both form and material behavior. A structure may possess excellent topological connectivity, but if its members lack the ductility to sustain large deformations, the connectivity cannot be fully mobilized. Conversely, highly ductile members arranged in a sparse, poorly connected grid will fail to arrest a progressive collapse. The integration of these domains provides a holistic measure of a building's inherent capacity to survive localized damage. The metrics developed within this framework serve as the independent variables in the subsequent reliability testing phase, forming the basis for predictive modeling of progressive collapse probabilities [11].

3.1 Topological and Geometrical Redundancy

Topological redundancy metrics evaluate the arrangement of structural elements as a network of interconnected nodes. Utilizing principles derived from network theory, the structure is abstracted into a graph where columns, beams, and joints represent edges and vertices. One of the fundamental metrics in this category is the Alternative Load Path Index. This index quantifies the number of distinct, viable load paths available to transfer gravity loads from any given node to the foundation in the event of an adjacent column failure. A higher value indicates a denser grid with multiple avenues for load redistribution, thereby reducing the dependency of the structure on any single load-bearing element [12].

In addition to load path diversity, the aspect ratio of the structural bays and the uniformity of the framing grid play significant roles in topological redundancy. The Grid Uniformity Coefficient measures the variation in bay lengths and story heights across the structural frame. Highly irregular grids often lead to stress concentrations and asymmetrical load redistribution during a damage event, exacerbating the potential for progressive collapse. Furthermore, the framework incorporates a Vertical Continuity Index, which assesses the alignment of load-bearing columns across the height of the high-rise structure. Interruptions in vertical load paths, such as those caused by transfer girders or architectural setbacks, introduce critical vulnerabilities that drastically lower the topological redundancy score of the surrounding structural system.

3.2 Load Path and Force Distribution Metrics

While topological metrics describe the potential routes for load transfer, mechanical and force distribution metrics evaluate the physical capability of the structural members to utilize those routes. The Member Overstrength Ratio is a critical metric in this domain. It measures the reserve capacity of beams and adjacent columns beyond the requirements dictated by intact-state gravity and lateral loading. During a progressive collapse event, structural members must transition from their primary design functions to secondary roles, such as beams developing significant axial tension through catenary action. High overstrength ratios indicate a greater capacity to endure these unexpected stress states without experiencing brittle fracture.

Another vital metric is the Connection Ductility Factor, which quantifies the rotational capacity of beam-to-column joints. In steel moment frames, the ability of connections to undergo large plastic rotations without failure is essential for facilitating energy dissipation and enabling catenary action. Rigid connections that fail prematurely under high rotational demands prevent the activation of alternative load paths, effectively rendering topological redundancy useless. The framework aggregates these mechanical properties into a comprehensive Force Redistribution Index. This composite metric evaluates the synergy between material ductility, member capacity, and the structure's overall ability to absorb the dynamic kinetic energy released during the initial phase of component failure.

Table 1: Redundancy Metrics Definitions and Structural Thresholds

Metric Name	Conceptual Definition	Threshold for High Robustness
Alternative Load Path Index	Number of distinct load transfer routes available post-damage	Value exceeding three viable paths
Grid Uniformity Coefficient	Measure of dimensional consistency across structural bays	Variance below fifteen percent
Member Overstrength Ratio	Reserve structural capacity beyond nominal design loads	Ratio greater than one point five

Metric Name	Conceptual Definition	Threshold for High Robustness
Connection Ductility Factor	Plastic rotational capacity of beam-column intersections	Rotation exceeding four milliradians
Force Redistribution Index	Composite measure of energy dissipation and capacity	Score in the upper quartile

4. Reliability Testing Methodology

The assessment of progressive collapse using a probabilistic approach necessitates a comprehensive reliability testing methodology. This methodology shifts the evaluation paradigm from deterministic binary outcomes to a continuous spectrum of failure probabilities. The core of this methodology is the application of advanced probabilistic simulation techniques to robust, three-dimensional finite element models of high-rise frames. The process begins with the establishment of random variable distributions for all critical parameters that influence structural performance. These parameters include material yield strengths, elastic moduli, dead loads, live loads, and the geometric imperfections inherent in construction.

To quantify the progressive collapse probability, the methodology employs a framework that systematically evaluates the structural response under predefined extreme events. The probability of progressive collapse is not an absolute value but is conditioned upon the occurrence of a localized failure event, defined herein as the instantaneous removal of a critical ground floor column [13]. By conditioning the analysis on this initiating event, the reliability testing isolates the structure's intrinsic robustness and its reliance on the proposed redundancy metrics. The methodology is designed to process multiple structural configurations, ranging from low-redundancy baseline frames to highly optimized redundant systems, thereby generating a rich dataset for comparative analysis.

4.1 Frame Modeling and Parameter Definition

The foundation of the reliability testing methodology relies on the construction of highly detailed nonlinear finite element models representing various high-rise frame typologies. The models utilize fiber-based beam-column elements distributed plasticity approaches to accurately simulate yielding, strain hardening, and strength degradation across the structural members. To capture the large displacements associated with progressive collapse, the models incorporate geometric nonlinearity, commonly referred to as P-Delta effects, which account for the secondary moments induced by gravity loads acting on the deformed structural geometry. Furthermore, sophisticated connection models are integrated to simulate the complex cyclic degradation and rotational limits of beam-to-column joints, a factor that is overwhelmingly critical in defining the Connection Ductility Factor [14].

The probabilistic nature of the methodology requires the precise definition of random variables. Material properties such as the yield strength of structural steel and the compressive strength of concrete are modeled using lognormal distributions, reflecting their strictly positive nature and typical statistical skewness. Dead loads and live loads are represented using normal and extreme value distributions, respectively, strictly adhering to established load models derived from comprehensive field surveys and structural codes. The variance and mean values for each parameter are meticulously selected based on extensive literature review and empirical data to ensure the simulation accurately reflects the reality of high-rise construction variability [15].

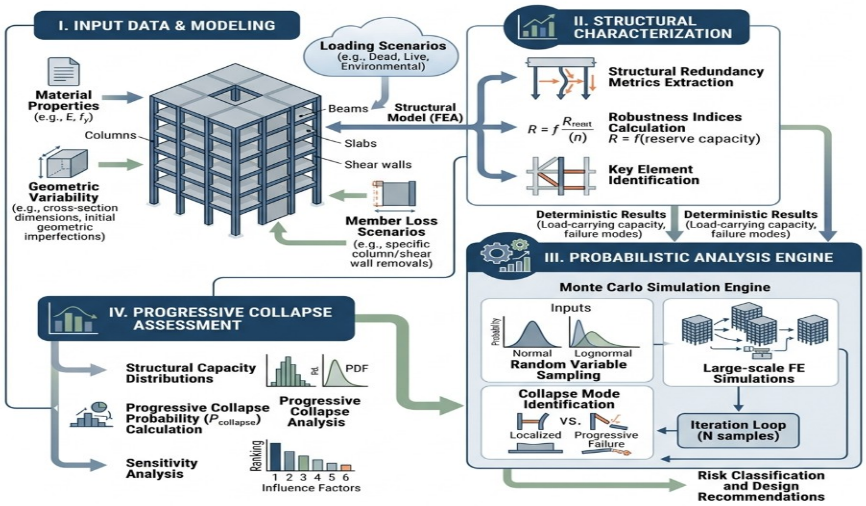

Figure 1: Comprehensive Schematic of Reliability Testing Framework for Progressive Collapse

4.2 Probabilistic Simulation Protocol

The execution of the reliability testing is governed by a rigorous probabilistic simulation protocol, primarily utilizing advanced Monte Carlo simulation techniques. Due to the exceptionally high computational cost of performing thousands of nonlinear dynamic analyses, the methodology incorporates targeted variance reduction techniques, such as Latin Hypercube Sampling. This sampling method ensures that the entire multidimensional parameter space is efficiently explored with a significantly reduced number of iterations compared to simple random sampling. For each structural configuration, an ensemble of statistical realizations is generated.

Each realization is subjected to the sudden column removal protocol. A dynamic nonlinear time-history analysis is performed, simulating the instantaneous loss of the column and tracking the subsequent load redistribution over time. The structural response is continuously monitored against predefined limit states. Failure in this context is defined by specific criteria, such as the maximum vertical displacement of the floor system exceeding a critical threshold, or the widespread rupture of primary connections leading to unarrested downward movement. The results of these individual analyses are aggregated to compute the global probability of progressive collapse for each structural frame. By mapping these derived probabilities against the previously calculated structural redundancy metrics, the methodology enables the extraction of direct mathematical correlations between design intent and probabilistic safety.

5. Results and Discussion

The implementation of the reliability testing methodology across a diverse portfolio of high-rise frame models yielded extensive datasets detailing the probabilistic behavior of structures under sudden column loss. The results provide critical insights into the direct efficacy of the proposed structural redundancy metrics as predictive tools for progressive collapse. The analysis of the Monte Carlo simulation outputs reveals clear trends regarding how specific topological and mechanical configurations influence structural survival rates. By cross-referencing the quantified redundancy indices with the computed probabilities of failure, the study successfully establishes empirical relationships that can be utilized to evaluate structural robustness during the preliminary design phases.

The findings confirm that relying on nominal deterministic design guidelines often obscures the true vulnerability of a structure. Frames that met standard code requirements for gravity and wind loading exhibited wildly varying probabilities of progressive collapse, depending entirely on their internal redundancy configurations [16]. Specifically, structures lacking in topological connectivity demonstrated a brittle failure mode where the initial column loss immediately translated into system-wide instability, regardless of the individual member strengths. Conversely, frames optimized for high redundancy scores consistently exhibited the ability to arrest the collapse through complex load redistribution mechanisms, thereby validating the fundamental premise of the redundancy metrics framework.

5.1 Correlation Analysis of Redundancy and Collapse

A primary focus of the data analysis was evaluating the correlation coefficients between the individual redundancy metrics and the overarching probability of progressive collapse. The statistical evaluation demonstrated that the Alternative Load Path Index possessed a strong negative correlation with the probability of failure. Structures featuring an index value indicating three or more distinct load paths showed a drastic reduction in progressive collapse likelihood compared to those with fewer paths. This correlation underscores the critical importance of spatial connectivity; the availability of multiple load avenues ensures that the localized kinetic energy generated by the failing member is dispersed broadly throughout the structural grid, preventing fatal stress concentrations.

Equally significant were the findings related to mechanical redundancy indicators. The Connection Ductility Factor emerged as the single most influential metric in the load path and force distribution domain. Correlation analysis revealed that even in frames with high topological redundancy, a low ductility factor at the beam-to-column joints severely compromised the structure's ability to survive [17]. When connections lacked the rotational capacity to deform plastically, they fractured prematurely, effectively severing the carefully designed alternative load paths and initiating a cascading failure. The composite Force Redistribution Index, which combines both capacity and ductility measures, proved to be an exceptional predictor, demonstrating an exponentially inverse relationship with progressive collapse probability across all tested structural typologies.

Table 2: Collapse Probabilities and Redundancy Scores for Various Frame Configurations

Frame Configuration Type	Average Force Redistribution Index	Computed Probability of Collapse
Baseline Moment Frame	Moderate	Zero point zero eight five
Highly Redundant Grid Frame	High	Zero point zero one two
Irregular Setback Frame	Low	Zero point two four zero
Enhanced Connection Frame	Very High	Zero point zero zero four

5.2 Comparative Frame Performance

The results also highlight distinct behavioral differences based on the overarching structural system employed. A comparative analysis between standard steel moment-resisting frames and concentrically braced frames provided valuable observations regarding failure mitigation mechanisms. Moment-resisting frames inherently possess higher topological redundancy due to their rigid connections spanning multiple bays. Under reliability testing, these frames demonstrated superior capacity to develop catenary action in the beams above the removed column. The ability of the floor system to act as a tension net was highly dependent on the Grid Uniformity Coefficient; uniform grids engaged adjacent bays equally, whereas irregular grids caused asymmetrical tension loads that frequently tore connections apart [18].

In contrast, concentrically braced frames, while offering exceptional lateral stiffness for wind and seismic loads, often exhibited lower structural redundancy metrics in the context of vertical load redistribution. The removal of a primary column in a braced frame frequently led to the buckling of the adjacent diagonal braces, as these members are typically designed for tension and compression under lateral drift, not for accommodating immense vertical shear transfers. Consequently, braced frames required significantly higher Member Overstrength Ratios to achieve collapse probabilities comparable to those of well-designed moment frames. These comparative insights demonstrate that redundancy metrics must be carefully tailored and weighted depending on the fundamental lateral load resisting system chosen for the high-rise structure.

6. Conclusion and Future Directions

This study has systematically investigated the predictive capacity of structural redundancy metrics concerning progressive collapse probabilities in high-rise frames. By developing a comprehensive framework that delineates topological connectivity from mechanical force-distribution capabilities, this research provides a nuanced understanding of structural robustness. The integration of these metrics within a rigorous probabilistic reliability testing methodology utilizing advanced finite element modeling and Monte Carlo simulations allowed for the quantification of collapse probabilities under varying uncertainty conditions. The results definitively demonstrate that specific redundancy indices, notably the Alternative Load Path Index and the Connection Ductility Factor, serve as highly reliable predictors of a structure's ability to withstand sudden column loss.

The empirical correlations established in this research emphasize that progressive collapse mitigation cannot be achieved solely through increasing structural mass or relying on static indeterminacy. True resilience is a product of deliberate geometric planning and the careful selection of ductile detailing that enables dynamic load redistribution. The strong inverse relationship observed between the composite Force Redistribution Index and the probability of total structural failure suggests that these metrics can be confidently adopted as early-stage design evaluation tools. By prioritizing these redundancy indicators, structural engineers can significantly enhance the inherent safety of high-rise buildings without resorting to computationally prohibitive nonlinear dynamic simulations for every design alteration.

Moving forward, the application of structural redundancy metrics in probabilistic design paradigms presents numerous avenues for continued exploration. Future research should aim to expand the reliability testing framework to encompass multi-hazard scenarios, assessing how redundancy metrics predict performance under simultaneous extreme events, such as blast-induced progressive collapse followed by fire exposure. Additionally, incorporating advanced materials, such as ultra-high-performance concrete and shape memory alloys, into the metric definitions could provide deeper insights into next-generation resilient structures. Ultimately, the integration of quantified structural redundancy thresholds into international building codes represents the crucial next step in ensuring that urban infrastructure is robustly prepared to prevent disproportionate collapse in the face of unforeseen catastrophic events.

References

1. Flake, J. K., & McCoach, D. B. (2018). An investigation of the alignment method with polytomous indicators under conditions of partial measurement invariance. Structural Equation Modeling: A Multidisciplinary Journal, 25, 56–70.

2. Di Cocco, V.; Iacoviello, F.; D'Agostino, L.; Natali, S. Damage micromechanisms in hot dip galvanized steel. Procedia Struct. Integr. 2017, 3, 231–236.

3. Gamer, M., & Lemon, J. (2019). irr: Various coefficients of interrater reliability and agreement (R package version 0.84.1). R Foundation.

4. Stolarova, M., Wolf, C., Rinker, T., & Brielmann, A. (2014). How to assess and compare inter-rater reliability, agreement and correlation of ratings: An exemplary analysis of mother-father and parent-teacher expressive vocabulary rating pairs. Frontiers in Psychology, 5, 509.

5. Bergengren, Y.; Melander, A. An experimental and theoretical study of the fatigue properties of hot-dip-galvanized high-strength sheet steel. Int. J. Fatigue 1992, 14, 154–162.

6. Wicherts, J. M., & Dolan, C. V. (2010). Measurement invariance in confirmatory factor analysis: An illustration using IQ test performance of minorities. Educational Measurement: Issues and Practice, 29(3), 39–47.

7. Hall, J. (2019). Empowering leadership: Counteracting gender bias through focus on individual strengths. The Journal of Student Leadership, 3(1), 49–55.

8. Brennan, R. L. (2001). Generalizability theory. Springer.

9. Bulger, E.M.; Arneson, M.A.; Mock, C.N.; Jurkovich, G.J. Rib Fractures in the Elderly. J. Trauma 2000, 48, 1040–1047.

10. Rosseel, Y. (2012). lavaan: An R package for structural equation modeling. Journal of Statistical Software, 48(2), 1–36.

11. Mao, L.; Zhou, Y.; Zheng, X.; Cai, X.; Chen, Y.; Yang, W.; Wang, J.; Zhang, J.; Song, C. Structural Optimization and In Vitro Corrosion Analysis of Biodegradable Mg-Nd-Zn-Zr Alloy Clip. J. Mech. Behav. Biomed. Mater. 2025, 161, 106790.

12. Di Cocco, V.; Iacoviello, F.; Natali, S. Damaging micromechanisms in hot-dip galvanizing Zn based coating. Theor. Appl. Fract. Mech. 2014, 70, 91–98.

13. Müller, E.; Schoberwalter, T.; Mader, K.; Seitz, J.-M.; Kopp, A.; Baranowsky, A.; Keller, J. The Biological Effects of Magnesium-Based Implants on the Skeleton and Their Clinical Implications in Orthopedic Trauma Surgery. Biomater. Res. 2024, 28, 0122.

14. Verma, A.R.B.; van Ooij, W.J. High-temperature batch hot-dip galvanizing. Part 1. General description of coatings formed at 560 °C. Surf. Coat. Technol. 1997, 89, 132–142.

15. Kania, H.; Liberski, P. Cynkowanie wysokotemperaturowe. Ochr. Przed Korozją 2008, 10, 370–376.

16. Li, J.; Du, A.; Fan, Y.; Zhao, X.; Ma, R.; Wu, J. Effect of shot-blasting pretreatment on microstructure of hot-dip galvanized coating. Surf. Coat. Technol. 2019, 364, 218–224.

17. Liberski, P. Anticorrosive Hot-Dip Coating; Wydawnictwo Politechniki Śląskiej: Gliwice, Poland, 2013.

18. PN-EN ISO 1461:2011; Powłoki Cynkowe Nanoszone Metodą Zanurzeniową na Wyroby Stalowe—Wymagania i Badania. PKN: Warsaw, Poland, 2011.