



Quantitative Structural Retrofit Assessment Models for Strengthening Existing Steel Buildings Under Increased Load Demands

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Abstract

This study examined quantitative structural retrofit assessment models for strengthening existing steel buildings exposed to increased load demands. The problem addressed was the growing mismatch between the original design capacity of aging steel buildings and the higher structural demands created by occupancy intensification, heavy equipment installation, rooftop service additions, vertical expansion, functional conversion, and updated code requirements. The purpose of the study was to determine how load demand escalation, structural deficiencies, retrofit technique suitability, and retrofit decision drivers influence strengthening effectiveness and structural safety improvement. A quantitative, cross-sectional, case-based research design was adopted, using structured Likert-scale data from 210 technical respondents, including structural engineers, civil engineers, retrofit consultants, construction/project managers, and building assessors, all involved in steel building assessment or strengthening projects. The key variables were increased load demand, structural deficiency, retrofit technique suitability, retrofit decision drivers, and strengthening effectiveness. Data analysis was planned and conducted through descriptive statistics, Pearson correlation analysis, and multiple regression modeling. The findings showed strong agreement that retrofit assessment is necessary under increased load conditions, with mean scores of 4.18 for increased load demand, 4.09 for structural deficiency, 4.23 for retrofit suitability, 4.27 for retrofit decision drivers, and 4.31 for strengthening effectiveness. Connection weakness ranked as the leading structural deficiency ($M = 4.17$), while heavy equipment installation was the highest-ranked load escalation factor ($M = 4.26$). Connection strengthening was rated the most suitable retrofit technique ($M = 4.35$), and structural safety requirement was the highest decision priority ($M = 4.41$). Correlation results showed significant positive relationships between assessment variables and strengthening effectiveness, with coefficients ranging from $r = 0.593$ to $r = 0.711$, all at $p < .001$. Regression results further confirmed that the model explained 61.0% of the variance in strengthening effectiveness ($R^2 = 0.610$, $F(4,205) = 80.13$, $p < .001$), with retrofit suitability emerging as the strongest predictor ($\beta = 0.331$). The study implies that steel-building retrofit decisions should be guided by structured, data-based assessment models that align load demand, system deficiencies, intervention suitability, and safety-centered decision priorities to improve reliability and continued serviceability.

Keywords

Structural Retrofit Assessment; Existing Steel Buildings; Increased Load Demands; Strengthening Effectiveness; Reliability-Based Structural Safety.

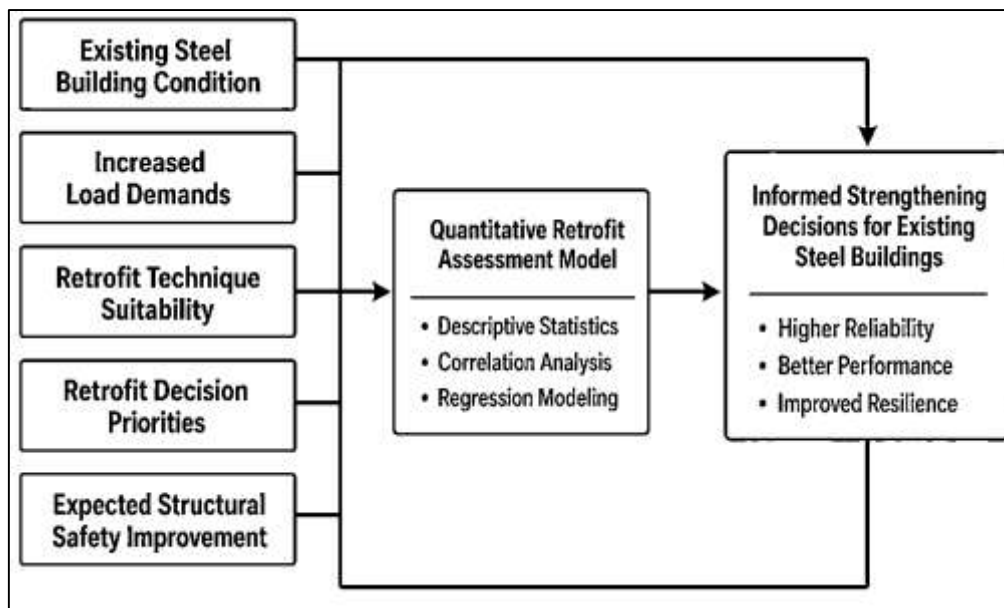
INTRODUCTION

Structural retrofit refers to the deliberate modification of an existing building so that its load-carrying system can achieve a required level of strength, stiffness, ductility, stability, or robustness under revised service and hazard conditions. In engineering literature, retrofit is closely linked with the assessment of existing structures, where inspection, analysis, testing, and performance verification are used to determine whether the current structural state remains acceptable or whether strengthening is necessary (Aljawhari et al., 2022). In steel buildings, retrofit assessment commonly addresses load-bearing adequacy, lateral resistance, connection behavior, progressive collapse resistance, and the reliability of members that have experienced long-term service exposure or changed functional demands. The topic has broad international significance because the global building stock contains a substantial number of steel structures that were designed under older codes, lower hazard assumptions, and different occupancy patterns than those applied today. This condition has been documented across several regions and building categories, including European industrial buildings, Iranian school buildings, and other classes of existing buildings evaluated under contemporary seismic and safety criteria (Cimellaro et al., 2010). The need for retrofit emerges when buildings are required to sustain increased gravity loads, revised lateral demands, abnormal actions, or enhanced post-event performance requirements. Existing-building evaluation has therefore expanded from simple code checking toward broader frameworks that integrate reliability, vulnerability, fragility, and resilience as measurable dimensions of structural safety and performance (Buda et al., 2022). Within this broader context, quantitative structural retrofit assessment models occupy a central place because they transform engineering observations into comparable variables that can be ranked, correlated, and interpreted systematically. Such models are especially important when building owners, engineers, and regulators need evidence-based justification for strengthening existing steel buildings rather than replacing them. The international relevance of this subject is reinforced by the convergence of aging infrastructure, densification of urban use, increased demand for continuity of operations, and stricter safety expectations applied to the built environment across regions and building typologies (Cao et al., 2022).

The concept of increased load demand is fundamental to the assessment of existing steel buildings because structural adequacy is always relative to the actions a building is expected to resist. Load demand may increase through changes in occupancy, addition of mechanical and rooftop equipment, vertical extensions, revised code-defined live loads, lateral-force reclassification, or alterations in operational use that introduce new combinations of dead, live, wind, seismic, thermal, or accidental effects (Andrews et al., 2009). In practice, a steel building that once performed acceptably can become structurally inadequate when these demands change while the original members, joints, and load paths remain unchanged. Research on existing structures repeatedly shows that vulnerability is often associated not only with physical deterioration but also with the mismatch between original design assumptions and current performance requirements. Many existing steel structures are exposed to degradation and increasing loads, making reliability assessment a necessary basis for determining whether a structure may remain unchanged, requires strengthening, or should be replaced. Steel industrial buildings have also been framed in the literature as requiring retrofit because older construction practices and inadequate seismic provisions can reduce structural performance under present-day loading expectations (Tartaglia, Milone, Prota, et al., 2022). This issue is not limited to seismic regions. Progressive collapse studies on steel frames have shown that abnormal load scenarios and redistribution demands can expose weaknesses that remain hidden under ordinary service conditions. The international significance of increased load demand also stems from the fact that adaptive reuse and operational intensification are now common in commercial, institutional, industrial, and public buildings. As the intended use of a building changes, the structure is required to accommodate higher reserve capacity, better deformation control, and more dependable connection performance than the original design may have provided (Sardari et al., 2020). For this reason, the literature increasingly treats increased load demand as a multi-dimensional engineering condition involving capacity deficiency, serviceability concerns, safety margin reduction, and the need for quantitatively defensible strengthening decisions.

Existing steel buildings present a distinct structural assessment challenge because their performance depends not only on member strength but also on connection behavior, redundancy, robustness, lateral-force-resisting configuration, detailing quality, and deterioration history (Ismail & El-Sokkary, 2020). Steel is valued for its high strength-to-weight ratio, ductility, prefabrication efficiency, and adaptability, yet these advantages do not eliminate the possibility of local weaknesses that govern overall performance. In older steel buildings, assessment frequently reveals connection deficiencies, limited ductile detailing, corrosion-related section loss, serviceability problems, instability concerns, and insufficient reserve strength under new loading patterns (Hessek et al., 2022). Progressive collapse research has reinforced the importance of robustness in existing steel frames by showing how the loss of a critical member can trigger disproportionate structural response when alternate load paths are weak or absent. Connection studies in buckling-restrained braced frames have further demonstrated that global frame performance is closely tied to local connection mechanics, since connection failure modes can prevent braces from developing the ductility assumed in design (Mohsenian et al., 2021). Steel moment-resisting frame studies have also proposed optimal retrofit models for brittle connections, underscoring the need to target connection vulnerability directly when evaluating seismic rehabilitation options. Reliability improvement studies on steel moment-resisting frames retrofitted with vertical link elements have shown that retrofit can be evaluated quantitatively in terms of system reliability rather than only by qualitative engineering judgment.

Figure 1: Quantitative Structural Retrofit Assessment Model for Existing Steel Buildings Under Increased Load Demands



These studies show that the condition of an existing steel building cannot be reduced to a single capacity number (O'Reilly et al., 2018). Its actual adequacy is shaped by the interaction among member demand ratios, connection hierarchy, drift response, redistribution capacity, and the reliability of lateral and gravity load paths under revised actions. This is why a retrofit assessment model must treat structural condition as a measurable construct that includes deterioration, overstress, connection vulnerability, redundancy, and the building's ability to sustain both ordinary and extraordinary load demands. In international literature, this multi-layered perspective is increasingly recognized as essential for credible strengthening decisions in existing steel buildings and related structural systems (Nadolski et al., 2022).

The retrofit options available for steel buildings are diverse, and the presence of multiple technically feasible interventions makes the assessment stage even more important. Strengthening strategies may involve adding concentrically braced frames, buckling-restrained braces, dampers, vertical links,

supplemental substructures, exoskeleton-type systems, member enlargement, plate strengthening, connection retrofitting, or roof-level alternate load-path systems designed to improve robustness. The literature consistently shows that no single retrofit technique is universally superior; suitability depends on the structural system, the governing deficiency, the nature of increased load demand, construction constraints, and the required performance objective (Ullah et al., 2022). Tailored retrofit measures have been proposed for industrial steel buildings using different combinations of counterbracing and dissipative bracing, illustrating how local and global retrofit actions can be selected according to building-specific deficiencies. Review studies on seismic retrofit of steel frame structures have highlighted the performance role of braces, dampers, and other strengthening devices in steel systems. Syntheses on buckling-restrained braced frames have emphasized their importance in seismic protection because of their strength, stiffness, and energy dissipation capacity (Park et al., 2018). Broader retrofit reviews have also described externally attached substructures as an upgrading strategy for existing frame buildings, emphasizing the need to improve structural performance while minimizing interference with occupancy and operations. Comparative studies on retrofit systems and state-of-the-art reviews have distinguished between local strengthening of individual elements and global interventions that reorganize a building's lateral and vertical response. Comprehensive reviews of seismic analysis, design, and retrofit have further shown that modern retrofit design now sits at the intersection of analysis, detailing, and performance assessment (Samadian et al., 2019). This body of work makes clear that retrofit selection is not merely a technical preference; it is an evaluative process involving structural demand, safety expectation, constructability, cost efficiency, and compatibility with the existing steel system. For a study focused on quantitative structural retrofit assessment models, this diversity of retrofit methods strengthens the need for a framework that ranks technique suitability under different load-demand scenarios rather than treating all strengthening strategies as functionally equivalent.

A major development in the international research landscape is the movement from purely descriptive engineering appraisal toward quantitative assessment frameworks that express safety and retrofit adequacy through measurable indicators. Reliability, fragility, vulnerability, and resilience have become recurring analytical lenses for evaluating existing structures and judging the effectiveness of strengthening interventions. Analytical frameworks for quantifying disaster resilience have linked structural performance and recovery in ways that expanded assessment beyond simple damage states. In seismic retrofit research, resilience has been evaluated using vulnerability curves for existing and retrofitted buildings, showing how strengthening can be assessed through measurable changes in expected performance (Vona et al., 2021). Practical seismic retrofit strategies have also been developed on the basis of reliability and resiliency analysis for existing steel school buildings, further demonstrating the value of probability-informed assessment for strengthening decisions. Fragility-oriented retrofit design approaches have shown that building-level fragility reduction can be mapped against capacity-demand improvement in case-study structures. Reliability-based studies have also evaluated retrofitted steel moment-resisting frames and buckling-restrained braced frames through stochastic and system-based methods, illustrating that retrofit effectiveness can be assessed through quantifiable reliability improvement (Wigle & Fahnestock, 2010). Taken together, these studies establish that retrofit assessment is strongest when it moves beyond binary judgments of safe and unsafe and instead measures the relative improvement associated with different retrofit actions. This matters directly for existing steel buildings under increased load demands because the engineer must often compare multiple alternatives under uncertainty rather than verify one fixed design case. Quantitative models enable that comparison by converting load escalation, structural deficiencies, retrofit feasibility, and expected safety improvement into analyzable relationships. Such a perspective aligns naturally with descriptive statistics, correlation analysis, and regression modeling, since those methods can identify dominant decision drivers, estimate the strength of relationships among variables, and explain which combinations of assessment factors are most strongly associated with retrofit effectiveness (Zhang et al., 2020).

Another important feature of the literature is the growing use of case-study-based assessment to capture the real conditions of existing buildings, since retrofit decisions are shaped by context-specific interactions among structural form, defect pattern, hazard exposure, and operational constraints. Case-

study research has been especially prominent in retrofit and vulnerability assessment because the behavior of existing buildings is not fully described by idealized code-compliant models. Seismic assessment and loss estimation studies on school buildings in Italy, vulnerability methodologies for existing buildings using structural data and monitored response, and steel-building retrofit case studies all demonstrate the value of detailed context-based evaluation in understanding the need for strengthening and the expected effect of interventions (Domaneschi et al., 2021). Full-building structural models and realistic scenarios have also been used to examine progressive collapse assessment and retrofit in steel buildings. Comparative performance assessment studies have evaluated buildings with and without retrofit strategies, while resilience-based retrofit studies have examined strategic buildings through broader performance-based criteria. Editorial syntheses in the field have highlighted the interconnected research agenda linking vulnerability assessment, retrofitting, numerical modeling, and experimental evidence in the contemporary built-environment literature (Dumaru et al., 2018). These studies collectively support a methodology in which expert-informed observations can be translated into structured variables representing building condition, load-demand escalation, retrofit suitability, decision priority, and expected safety improvement (Ferraioli et al., 2022). Such a design is particularly valuable when the thesis aims to analyze relationships statistically rather than only narrate engineering observations. A cross-sectional quantitative design allows these variables to be measured at one point in time across a defined respondent group or set of case observations, while descriptive statistics summarize their distribution, correlation analysis reveals association patterns, and regression modeling identifies which retrofit assessment dimensions most strongly explain strengthening outcomes. This methodological orientation reflects a mature strand of international assessment research that combines engineering specificity with quantitative inference (De Angelis & Pecce, 2015).

Within this literature, a clear scholarly space exists for a study centered specifically on quantitative structural retrofit assessment models for strengthening existing steel buildings under increased load demands. Existing research offers strong technical examinations of individual retrofit devices, seismic upgrading methods, robustness enhancement strategies, vulnerability assessment procedures, and reliability-based evaluation tools (Freddi et al., 2022). Less consolidated in the literature is a single quantitative framework that brings together the condition of existing steel buildings, the profile of increased load demands, the ranking of retrofit technique suitability, the prioritization of retrofit decision drivers, and the expected structural safety improvement in one integrated assessment model. Steel-focused studies often concentrate on one performance domain, such as seismic strengthening of industrial buildings, progressive collapse robustness, brittle-connection rehabilitation, or reliability improvement in a specific retrofitted frame system (Furtado et al., 2021). Broader building-retrofit studies contribute valuable concepts in fragility, resilience, and vulnerability, while review papers synthesize local-versus-global strategies and modern retrofit technologies. The present research area therefore sits at the intersection of these strands: it requires the engineering specificity of steel-building strengthening and the analytical structure of quantitative assessment modeling (Gkournelos et al., 2021). It also requires attention to increased load demand as a practical trigger for retrofit need, a factor that interacts with structural condition, feasibility constraints, and safety expectations rather than functioning as a standalone technical variable. Framed in this way, the introduction naturally points toward an assessment architecture in which expert responses, case-study evidence, and statistically analyzable variables are used to understand how retrofit choices are formed and how strengthening effectiveness can be evaluated systematically for existing steel buildings facing revised demands.

Background of the Study

The background of this study is rooted in the growing structural and operational pressure placed on existing steel buildings in modern built environments. Steel buildings have long been valued for their high strength-to-weight ratio, speed of construction, adaptability, and efficiency in spanning large spaces, making them widely used in industrial, commercial, institutional, and mixed-use developments. Many of these buildings, however, were designed according to the load requirements, occupancy expectations, material assumptions, and code provisions that existed at the time of their construction. Over time, the demands placed on such structures often change significantly. Buildings may undergo functional conversion, vertical expansion, installation of heavier mechanical systems,

rooftop equipment additions, storage intensification, occupancy increases, or code-driven reassessment of safety requirements. These changes can create load demands that exceed or closely approach the original design capacity of the existing structural system. In such situations, structural retrofit becomes a necessary engineering response for restoring adequacy, improving safety, and extending service life. The challenge is not simply whether a steel building needs strengthening, but how to assess that need systematically and how to determine which retrofit strategy is most suitable under a given set of structural conditions. Existing steel buildings often present complex conditions such as member overstress, corrosion, connection weakness, stability limitations, and serviceability concerns, all of which interact with increased load demand in ways that complicate decision-making. For that reason, retrofit planning requires more than routine inspection or isolated design checks; it requires a structured assessment model capable of evaluating technical, safety, and decision-related variables in an integrated manner. This study emerges from that need by focusing on quantitative structural retrofit assessment models for strengthening existing steel buildings under increased load demands. It is grounded in the idea that retrofit decisions should be informed by measurable indicators and systematic analysis rather than by informal judgment alone. By examining building condition, load escalation, retrofit suitability, safety expectations, and decision drivers within a quantitative framework, the study addresses an important problem in structural engineering practice where aging steel infrastructure must continue to perform under evolving functional and safety requirements.

Problem Statement

The problem addressed in this study arises from the growing mismatch between the original design capacity of many existing steel buildings and the increased load demands they are required to resist in present-day use. A considerable number of steel structures currently in service were designed for earlier operational conditions, lower occupancy intensities, lighter equipment loads, and older code assumptions. As buildings age and their functions evolve, they are frequently subjected to additional vertical and lateral demands resulting from renovation, expansion, equipment installation, storage intensification, occupancy conversion, and revised safety requirements. In many cases, these changes create structural conditions in which the building may no longer perform with the same margin of safety, serviceability, and reliability intended in the original design. The difficulty is that the need for retrofit in existing steel buildings is rarely determined by a single factor. It is influenced by the interaction among load escalation, structural deterioration, connection weaknesses, member inadequacy, stability concerns, feasibility of intervention, and expected safety improvement after strengthening. This creates a decision environment that is technically complex and often dependent on fragmented engineering judgment. In practice, retrofit decisions may be shaped by isolated inspections, code checks, or cost-driven considerations without a sufficiently integrated quantitative framework for evaluating the full range of relevant variables. As a result, there is a risk that strengthening needs may be underestimated, retrofit priorities may be poorly ranked, or selected interventions may not correspond effectively to the actual demands imposed on the building. The central problem, therefore, is the absence of a clearly structured quantitative assessment model that can systematically examine the condition of existing steel buildings, measure the impact of increased load demands, evaluate the suitability of retrofit strategies, and determine the factors that most strongly influence strengthening effectiveness. This study responds to that problem by focusing on the development of a quantitative understanding of retrofit assessment for existing steel buildings, where measurable variables can be analyzed to support more consistent, transparent, and technically grounded retrofit decision-making.

Objective-Based Paragraph

The objective of this study is to examine, in a systematic and quantitative manner, how structural retrofit assessment models can be used to strengthen existing steel buildings subjected to increased load demands. More specifically, the study seeks to identify the principal sources of increased load demand that place additional stress on existing steel structural systems and to determine how these demands influence the need for retrofit intervention. It also aims to assess the condition-related factors that define the structural adequacy of existing steel buildings, including issues such as overstress, deterioration, instability, and connection weakness, and to understand how these factors contribute to retrofit urgency. Another important objective is to evaluate the suitability of different retrofit strategies under varying load-demand scenarios so that strengthening decisions can be aligned more closely with

the actual needs of the structure rather than with general engineering preference alone. The study further aims to measure the relationship between retrofit assessment variables and expected strengthening outcomes, particularly in relation to structural safety improvement, performance enhancement, and retrofit decision priorities. Through the use of descriptive statistics, correlation analysis, and regression modeling, the research intends to determine which assessment factors are most influential in explaining strengthening effectiveness in existing steel buildings. In addition, the study is designed to provide an empirical basis for ranking the major drivers of retrofit decisions, such as load severity, structural condition, feasibility, and safety expectations, within a case-study-based framework. In this way, the study moves beyond a purely descriptive treatment of retrofit by organizing its objectives around measurable relationships and evidence-based evaluation. The overall objective is therefore not only to understand whether existing steel buildings require strengthening under increased load demands, but also to establish how quantitative assessment can support more accurate, consistent, and structured retrofit planning across real building conditions.

Research Hypotheses

The research hypotheses of this study are formulated to test the measurable relationships between increased load demands, the condition of existing steel buildings, retrofit assessment variables, and strengthening outcomes. Since the study is quantitative in design, the hypotheses serve as structured statements that guide the statistical examination of how different variables interact within the retrofit decision process. The first hypothesis proposes that increased load demand has a significant relationship with the need for structural retrofit in existing steel buildings. This hypothesis is based on the expectation that as buildings experience added loads from changing use, equipment installation, expansion, or revised design requirements, the probability of structural inadequacy and the necessity for intervention also increase. The second hypothesis proposes that structural condition deficiencies significantly influence the choice of retrofit strategy. This reflects the assumption that buildings with more severe forms of deterioration, instability, connection weakness, or member overstress will require more targeted or intensive strengthening measures. The third hypothesis states that retrofit assessment variables have a significant positive relationship with strengthening effectiveness and structural safety improvement. Here, the study assumes that assessment dimensions such as load severity, existing condition, feasibility, and suitability of intervention are directly associated with the expected success of retrofit implementation. The fourth hypothesis proposes that retrofit assessment variables significantly predict retrofit decision priorities in existing steel buildings. This means that the research expects certain factors to emerge as statistically meaningful drivers of how retrofit needs are ranked and acted upon in professional practice. Together, these hypotheses transform the research problem into testable propositions that can be examined through quantitative analysis. They create a direct link between the conceptual structure of the study and its empirical investigation by allowing the researcher to test whether the assumed relationships among variables are statistically supported. In this way, the hypotheses provide the analytical foundation for evaluating the strength, direction, and predictive value of the core constructs that define retrofit assessment in existing steel buildings under increased load demands.

Significance of the Research

The significance of this research can be understood from several interrelated perspectives that reflect its academic, technical, and practical value in the field of structural engineering.

- i. **Significance to structural engineering knowledge:** This study contributes to the body of knowledge on existing steel buildings by focusing specifically on quantitative structural retrofit assessment under increased load demands. It organizes retrofit decision-making into measurable variables and statistically analyzable relationships, which gives the topic a more structured analytical foundation.
- ii. **Significance to professional engineering practice:** The study is important for practicing structural engineers, retrofit consultants, and building assessors because it addresses how strengthening decisions can be made more systematically. By identifying the main factors associated with retrofit need, retrofit suitability, and expected safety improvement, the research supports technically grounded assessment rather than reliance on unstructured judgment.
- iii. **Significance to owners and facility managers:** For building owners, operators, and facility managers, the study offers a clearer understanding of why existing steel buildings may require

reassessment when their load conditions change. It helps frame retrofit not as an isolated repair action but as an evidence-based response to measurable structural and operational demands.

iv. **Significance to safety and performance evaluation:** The study has value in the evaluation of building safety because it examines how assessment variables relate to strengthening effectiveness and structural improvement. This makes the research relevant to decision environments where safe continued use of aging steel infrastructure is a central concern.

v. **Significance to quantitative research design in built-environment studies:** The use of descriptive statistics, correlation analysis, and regression modeling gives the study methodological significance. It demonstrates how a case-study-based quantitative approach can be applied to structural retrofit assessment in a way that captures both technical complexity and analytical clarity.

vi. **Significance to policy and institutional assessment frameworks:** The findings of this study may also be useful for institutions and organizations involved in inspection, maintenance planning, and structural evaluation because they highlight the major drivers that influence retrofit priority in existing steel buildings. This provides a basis for more transparent and consistent assessment criteria.

vii. **Significance to future academic investigation:** The study creates a research foundation for other scholars who may wish to investigate retrofit assessment in broader building categories, other structural materials, or more advanced analytical environments. By structuring retrofit assessment around quantitative relationships, it opens a pathway for deeper empirical work within structural engineering research.

LITERATURE REVIEW

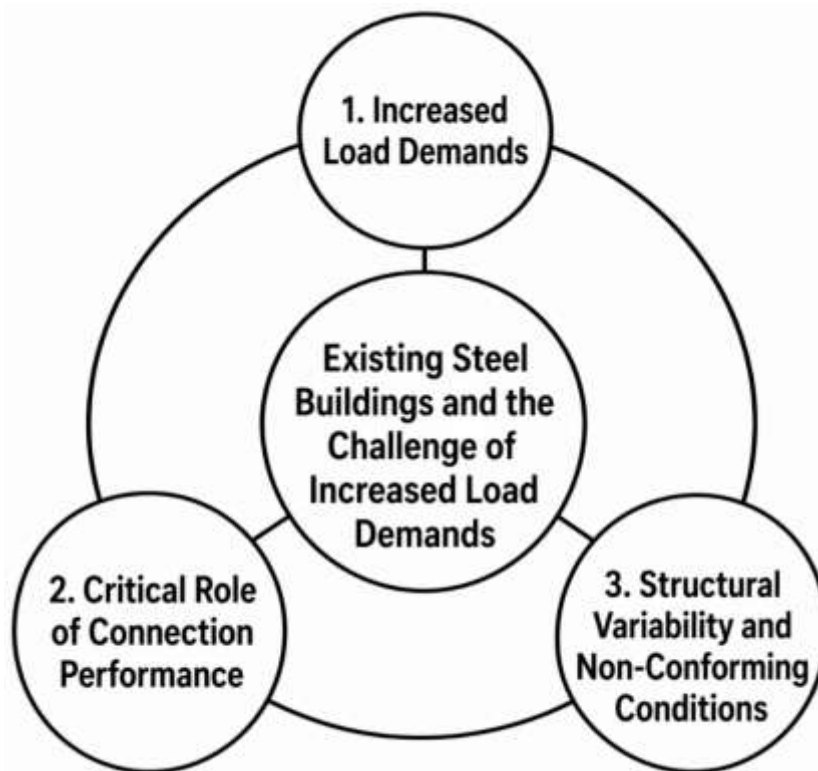
The literature on structural retrofit assessment has developed around the need to understand how existing buildings can continue to perform safely and effectively when exposed to conditions that differ from those assumed at the time of original design. In the context of existing steel buildings, the literature is especially concerned with the interaction among changing load demands, structural deficiencies, retrofit strategies, and performance expectations. Steel buildings occupy an important place in this body of work because they are widely used across industrial, commercial, and institutional settings and are often expected to remain in service even as their operational demands intensify over time. The literature shows that retrofit is not limited to repair or local strengthening alone; it is a broader structural intervention process that involves evaluating the adequacy of the existing system, identifying the sources of vulnerability, and selecting strengthening measures capable of restoring or improving safety, stiffness, ductility, and load resistance. A recurring theme in prior studies is that many existing buildings were designed for earlier use conditions and therefore require reassessment when they are subjected to increased loads arising from expansion, occupancy change, equipment addition, code revision, or evolving hazard expectations. Another major theme is that structural condition itself is multi-dimensional, involving member capacity, connection performance, deterioration, redundancy, robustness, and system-level behavior. The literature also shows that retrofit strategies vary significantly according to building type, governing deficiency, desired performance objective, and project constraints, which makes the assessment stage essential in determining which intervention is most suitable. More recent scholarship has expanded the discussion beyond traditional engineering appraisal by incorporating reliability, vulnerability, fragility, and resilience into the evaluation of existing structures and retrofit outcomes. This has encouraged a shift toward quantitative and performance-oriented approaches in which retrofit effectiveness can be assessed through measurable indicators rather than solely through descriptive engineering judgment. In this study, the literature review provides the intellectual foundation for examining increased load demands, structural deficiencies, retrofit technique suitability, and the role of quantitative assessment variables in explaining strengthening decisions and expected safety improvement in existing steel buildings.

Existing Steel Buildings and the Challenge of Increased Load Demands

Existing steel buildings form a substantial portion of the global built environment, particularly in industrial, commercial, warehouse, office, and institutional settings where long spans, speed of erection, and flexibility of interior planning made steel an attractive construction material. Many of these buildings continue to function long after their original design life assumptions, and their continued use has brought renewed attention to the difference between original design conditions and

present operational realities. The challenge is rooted in the fact that a large share of older steel buildings was designed according to earlier provisions that prioritized gravity and wind effects, while present-day evaluation often requires much stricter checks for seismic resistance, connection ductility, load redistribution, and reserve capacity. In practical terms, increased load demands emerge when buildings are converted to new uses, fitted with heavier service equipment, subjected to vertical expansion, or reevaluated under updated design standards that assign greater service and safety demands than those used at the time of construction. This means that the structural adequacy of an existing steel building cannot be understood only by reference to the original design drawings; it must be interpreted against current loading, detailing expectations, and actual in-service condition. The evolution of code philosophy has reinforced this point by showing that steel moment-resisting frames and related systems that once satisfied acceptable practice may no longer satisfy present requirements for ductility, continuity, and reliable inelastic behavior under severe loading. In that sense, the challenge of increased load demand is not merely a question of adding more force to an unchanged structure, but of reexamining whether the whole structural system, including its details and force-transfer mechanisms, remains appropriate for contemporary use and safety verification (Chi et al., 2006; Malley, 2007; Ashfaq & Manam, 2023). These conditions make the assessment of existing steel buildings a technically significant topic because structural demand escalation often develops gradually through changing use, while structural weakness may remain hidden until detailed evaluation exposes deficiencies in load paths, member capacity, or connection performance.

Figure 2: Existing Steel Buildings and The Challenge of Increased Load Demands



A second dimension of this challenge concerns the local vulnerabilities that control the performance of existing steel buildings when higher demands are imposed. In many older steel frames, beam-to-column connections are among the most critical regions because they govern deformation capacity, energy dissipation, and the reliability of moment transfer under intensified loading. Research on existing steel buildings has shown that retrofitting these connections is often necessary when original detailing does not provide the ductility or plastic rotation capacity required by newer performance expectations. For example, studies on side-plate rehabilitation and haunch-based strengthening

demonstrate that the improvement of existing welded moment connections is not only a local repair issue, but also a system-performance issue because connection behavior influences story drift, redistribution of internal forces, and the building's overall ability to sustain repeated load reversals or abnormal actions. This is especially relevant for buildings that were interrupted during construction, completed under changed provisions, or reassessed after recognition of brittle connection behavior in earlier design practice. At the same time, the problem is broader than seismic damage alone. Existing buildings subjected to increased functional demand may experience cumulative stress concentrations at joints even when the original members appear adequate at first inspection. Such conditions require engineers to examine the relationship between existing detailing and revised demand levels rather than assuming that member size alone can define structural sufficiency. The literature therefore treats existing steel buildings as systems whose critical weaknesses may lie in local connection response, especially where older welded details, insufficient continuity, or weak fracture resistance reduce the margin between acceptable service and unsafe behavior. This understanding has strengthened the argument that retrofit assessment must include detailed connection evaluation whenever increased load demand is under consideration, because the ability of the structural system to accommodate higher actions depends on the integrity of these local force-transfer zones as much as on the nominal strength of beams and columns (Asada et al., 2014; Chou et al., 2010; Sazzadul, 2023).

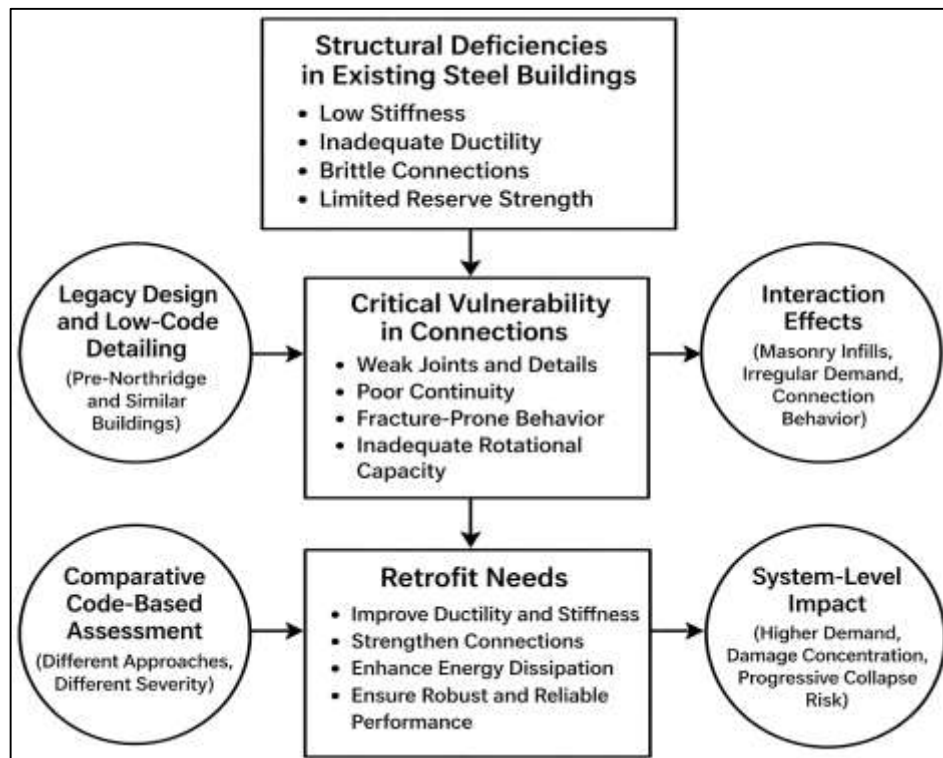
A third aspect of the literature emphasizes that existing steel buildings are not uniform objects but highly variable structural systems whose response to increased load demand depends on age, geometry, irregularity, connection typology, construction quality, and the interaction between local and global behavior. This variability explains why assessment cannot rely on a single generalized strengthening rule. In older multi-storey steel buildings, it is common to find combinations of moment-resisting frames, concentrically braced frames, and non-conforming joints within the same structure, creating a mixed performance profile in which some elements may appear satisfactory while others govern the overall deficiency. Studies of non-code-conforming steel buildings have shown that the original design of many such structures was based mainly on gravity and moderate wind effects, leaving them poorly prepared for present-day seismic verification or other intensified demands associated with occupancy changes and stricter performance requirements. Under those circumstances, increased load demand should be understood not only as an addition of mechanical or occupancy load, but also as an increase in the level of structural performance that society, regulators, and owners now expect from buildings that remain in use. This means that retrofit assessment must bridge two questions at once: whether the building can resist greater actions, and whether its current configuration can do so with dependable system behavior. Case-based research on non-code-conforming steel joints and multi-storey steel frames shows that local deficiencies in welds, continuity, and connection configuration can significantly reduce global performance, making strengthening decisions dependent on careful integration of inspection, modeling, and retrofit design. As a result, the literature positions existing steel buildings as structurally diverse and often demand-sensitive assets that require quantitative assessment when increased loads, revised codes, or changed use conditions place new expectations on their load-carrying system (Khaled, 2021; Tartaglia, Milone, D'Aniello, et al., 2022). This framing directly supports the need for a focused review of existing steel buildings as the starting point for understanding retrofit assessment under increased load demands.

Structural Deficiencies and Retrofit Needs in Steel Buildings

Structural deficiencies in existing steel buildings are typically revealed when the original load-resisting system is examined against present-day demands rather than against the assumptions that governed the initial design. Many steel moment-resisting frames and mixed steel framing systems constructed before the widespread adoption of modern seismic and performance-based provisions were proportioned mainly for gravity loads, moderate wind actions, and serviceability expectations that no longer represent current engineering requirements. Under contemporary assessment frameworks, those buildings frequently exhibit low lateral stiffness, inadequate energy dissipation capacity, brittle joint behavior, and limited reserve strength once realistic inelastic demand is considered. This problem is especially evident in pre-Northridge and similarly low-code steel buildings, where vulnerable beam-to-column connections, partial-joint-penetration splice details, and insufficient continuity provisions can concentrate damage and increase collapse risk. Case-based assessment research on a 35-story steel

building with pre-Northridge connection details showed that a structure designed under older practice can remain highly vulnerable once evaluated with modern performance-based procedures, particularly because brittle connection response and unfavorable local demand concentrations alter the expected global behavior of the frame. Parallel work on the seismic assessment of existing steel frames with masonry infills also demonstrated that seemingly secondary features, such as infill interaction, can substantially modify stiffness, force transfer, and damage concentration patterns, making deficiencies more complex than a simple member-capacity shortfall. These findings indicate that deficiency identification in steel buildings must address both the original design philosophy and the current structural configuration, including interaction between frame elements, joints, infill panels, and irregular demand distribution. In other words, retrofit need emerges not only when members are weak in a nominal sense, but when the actual structural system lacks the ductility, robustness, and dependable response required to sustain contemporary loading scenarios with acceptable performance. This makes structural deficiency a system-level concept rather than a purely element-by-element condition, and it explains why retrofit assessment in existing steel buildings must begin with a detailed understanding of how legacy detailing interacts with present demand and expected failure modes (Araújo & Castro, 2017; Sarno & Wu, 2020).

Figure 3: Structural Deficiencies and Retrofit Needs In Existing Steel Buildings



A second dimension of retrofit need is the concentration of vulnerability in steel connections and associated force-transfer zones, which often govern whether a building can safely accommodate increased load demand after years of service, alteration, or code re-evaluation. In existing steel structures, damage is not always initiated by gross yielding of major members; it often begins in joints where stiffness incompatibility, fracture-prone details, poor weld toughness, weak panel zones, inadequate continuity, or insufficient rotational capacity interrupt the intended development of ductile frame action. This is why many retrofit studies focus on connection rehabilitation as a central rather than secondary issue. Research on seismic upgrading of steel moment-resisting frames by means of friction devices showed that retrofit can be designed to reduce frame deformations and dissipate energy without relying exclusively on the original yielding hierarchy of older members and joints. Such findings are important because they present retrofit as a response to deficiency patterns embedded in

the existing frame rather than as a generic strengthening exercise. In a different but related line of inquiry, numerical and experimental work on progressive-collapse mitigation of steel beam-column joints using steel plates identified weak regions and critical issues that controlled the spread of collapse, reinforcing the argument that local connection weakness can determine whether the whole structural system retains continuity after abnormal loading (Gaiotti et al., 2022). The same concern appears in broad reviews of steel connection design, which emphasize that connection behavior strongly influences global structural response and that deficiencies in connection design or detailing can compromise the intended performance of the entire building. When these insights are read together, they show that retrofit need in steel buildings often arises from the inability of existing joints to sustain modern levels of deformation, tension, cyclic demand, and redistribution. This means that buildings can appear adequate at the level of member size and still remain deficient because the joints lack the reliability needed for robust frame action. The literature therefore positions connection vulnerability as one of the most decisive triggers for retrofit in existing steel buildings, especially where increased load demand or extreme-event verification requires dependable load transfer beyond the assumptions of original practice (Gutiérrez-Urzúa et al., 2021; Manam & Ashfaq, 2022).

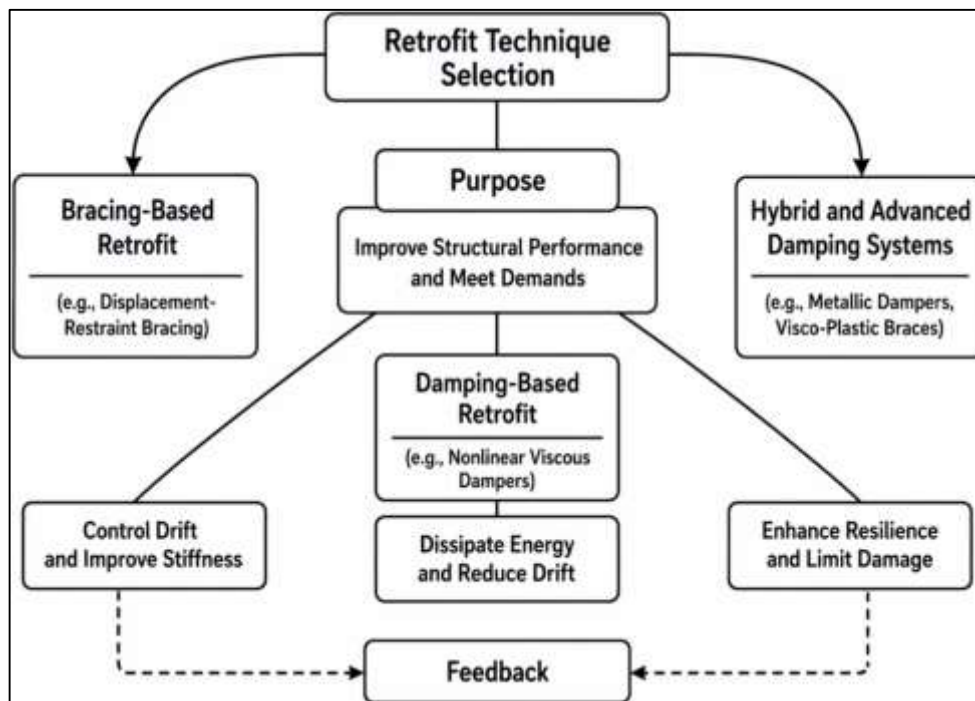
A third issue concerns the way retrofit needs are prioritized once deficiencies have been identified. Existing steel buildings rarely present one isolated shortcoming; they usually display a combination of stiffness deficiency, inadequate ductility, irregular force distribution, nonconforming detailing, vulnerability to progressive collapse, and uncertainty in code-based capacity estimates. For that reason, retrofit assessment increasingly requires comparative and code-informed judgment rather than simple verification of one parameter. Recent comparative analysis of code-based approaches for seismic assessment of existing steel moment-resisting frames showed that the definition of component capacity, slenderness limits, and modelling assumptions can meaningfully alter the perceived severity of deficiency, which in turn affects retrofit priorities and intervention selection. This confirms that retrofit need is partly technical and partly methodological, because the assessment framework itself shapes how the building's weaknesses are interpreted. In practical terms, the need for strengthening becomes strongest where several shortcomings interact: low-code detailing reduces ductility, irregular demand magnifies deformation concentration, local connection weakness interrupts redistribution, and older design assumptions fail to reflect present hazard or occupancy requirements (Güneyisi et al., 2014). The literature also shows that masonry infills, supplemental devices, or local upgrading measures can either aggravate or alleviate these interactions depending on how well the retrofit strategy matches the underlying deficiency pattern. Consequently, retrofit need in steel buildings should not be framed only as a reaction to visible distress or failed checks, but as a structured response to interacting vulnerabilities that lower the building's reliability under contemporary service and hazard conditions. From a literature-review perspective, this establishes a clear rationale for studying structural deficiencies as a separate subsection: the decision to strengthen an existing steel building depends on how deficiency is defined, where it is located, how it changes system behavior, and which analytical framework is used to evaluate it. The literature thus supports a deficiency-based understanding of retrofit need in which joints, frame configuration, code nonconformity, and demand amplification together determine why existing steel buildings require carefully targeted strengthening interventions (Alrubaidi & Alhammadi, 2022; Wang et al., 2017).

Structural Retrofit Techniques for Steel Building Strengthening

The literature on structural retrofit techniques for steel building strengthening shows that retrofit is not a single intervention method but a family of strategies selected according to the deficiency pattern, load-demand profile, target performance level, and practical constraints of an existing structure. In steel buildings, strengthening techniques are generally intended to improve one or more of the following system attributes: lateral stiffness, ductility, energy dissipation, drift control, connection reliability, and post-yield stability. Earlier retrofit practice often emphasized direct member strengthening or local joint repair, but the literature has increasingly shifted toward system-oriented solutions that alter structural response through added braces, damping mechanisms, and supplemental energy dissipation devices. This shift is important because many existing steel moment-resisting frames do not require simple enlargement of members alone; rather, they require a redistribution of seismic demand and a reduction of deformation concentration across the frame. One example is displacement-restraint bracing, which

was proposed as a retrofit technique for steel moment frames in order to control interstory displacement without sacrificing the inherent energy absorption characteristics of the original frame. In this approach, the brace does not behave like a conventional stiff brace that immediately attracts high force and amplifies column demand; instead, the delayed activation mechanism improves drift control while maintaining a more balanced structural response. The significance of this technique lies in its attempt to solve a recurring retrofit problem in steel buildings, namely that conventional stiffening can reduce deformation but may also produce undesirable force concentration in key members and joints. The literature therefore treats advanced bracing strategies as an important class of retrofit intervention because they allow engineers to improve seismic performance while managing the side effects of excessive stiffness increase. In this sense, steel building strengthening is framed not merely as adding resistance, but as designing a modified structural behavior that can better accommodate increased demand and reduce the likelihood of damaging response mechanisms under strong excitation (Hou & Tagawa, 2009). This systems-based understanding provides a useful foundation for evaluating retrofit techniques in existing steel buildings.

Figure 4: Structural Retrofit Techniques for Steel Building Strengthening



A second major category of retrofit techniques in the literature involves the use of supplemental damping devices, which are especially valued in steel buildings because they can reduce drift, dissipate energy, and improve performance without necessarily forcing widespread yielding of the primary structural members. Nonlinear viscous dampers have received considerable attention in this regard because they can be integrated into steel moment-resisting frames through bracing arrangements that convert interstory movement into damper action. Experimental and numerical studies of steel buildings equipped with nonlinear viscous dampers show that this strategy can achieve significant drift reduction and improved damage control even when the original moment frame is not proportioned to resist the full seismic demand by strength alone. This is an important finding for retrofit practice because many existing steel buildings were designed under older provisions and may not be economical to strengthen through large-scale member replacement. Instead, adding dampers offers a means of enhancing response through controlled energy dissipation. The literature has also advanced from simply proving the effectiveness of dampers to developing design procedures that identify suitable damper characteristics and retrofit levels for low-, medium-, and high-rise steel structures. This line of work is significant because it turns damping from a conceptual improvement

into a structured retrofit method capable of supporting performance targets, cost-conscious intervention planning, and rational placement decisions. In essence, damping-based retrofit techniques show that steel building strengthening can be achieved by modifying dynamic behavior rather than only increasing static resistance. This makes such techniques especially relevant for existing buildings where construction interruption, force redistribution, and preservation of usable space are important concerns. The literature therefore presents viscous damping as one of the most technically flexible retrofit approaches available for steel buildings, particularly when the objective is to improve seismic performance while limiting adverse effects on the existing gravity and lateral load-resisting system (Bahmani & Zahrai, 2019; Dong et al., 2016). Through this perspective, strengthening becomes a problem of response management as much as one of capacity enhancement.

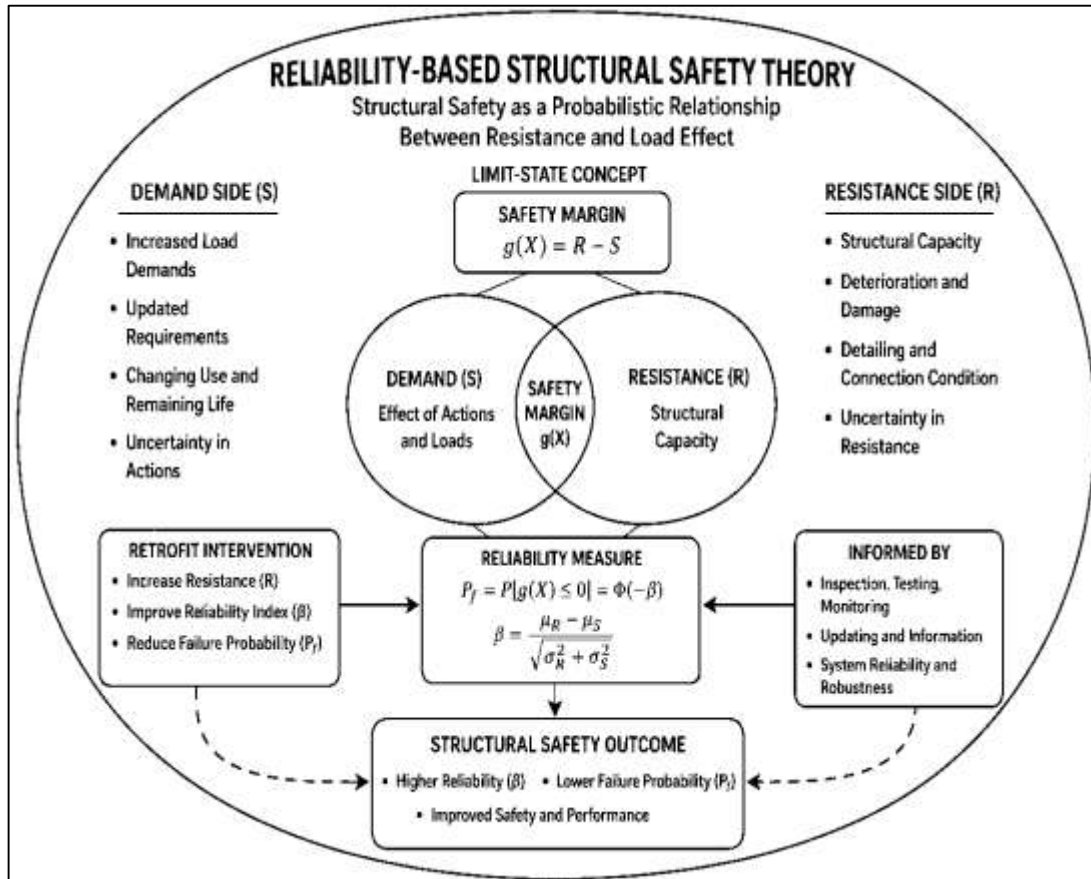
More recent literature expands the range of retrofit techniques by introducing metallic dampers and advanced brace-damper hybrids that aim to combine replaceability, stable hysteresis, drift mitigation, and resilience-oriented performance. A notable direction in this research is the development of specialized dampers that can be installed in steel moment-resisting frames to reduce damage concentration and improve post-earthquake functionality. One example is the varied yielding cross-section damper, which was proposed specifically for retrofitting steel moment-resisting frames and designed to avoid plastic concentration that often affects more conventional metallic devices. The advantage of this technique is not only its contribution to strength and drift control, but also its capacity to distribute yielding more effectively and permit convenient replacement after major seismic events. This makes it especially relevant for existing steel buildings where maintainability and controlled damage are important aspects of retrofit selection. Another important development is the use of advanced visco-plastic braces in tall steel buildings (Zhai et al., 2022). These hybrid devices combine different damping mechanisms in series so that the retrofit system can reduce drift, manage peak structural forces, and improve the overall resilience of the frame. The literature indicates that this class of retrofit technique is particularly valuable for taller steel buildings, where simple stiffening approaches can generate undesirable increases in member forces and floor accelerations. By integrating frictional and viscoelastic behavior within a brace-based retrofit system, advanced visco-plastic braces offer a more nuanced control of building response and broaden the available toolkit for strengthening steel structures with different height profiles and performance requirements. Taken together, these studies show that structural retrofit techniques for steel building strengthening have evolved from traditional strengthening measures toward more behavior-sensitive interventions that combine energy dissipation, controlled force transfer, and targeted improvement of deformation patterns. This evolution is directly relevant to the present study because it demonstrates that retrofit technique suitability must be assessed against building condition and load-demand characteristics rather than assumed universally. The literature therefore supports a comparative understanding of steel retrofit techniques in which bracing, damping, and hybrid systems are evaluated according to how effectively they strengthen the structure while preserving balanced and reliable system behavior (Bae et al., 2022; Binte & Sazzadul, 2022).

Theoretical Framework: Reliability-Based Structural Safety Theory

Reliability-Based Structural Safety Theory provides the most appropriate theoretical foundation for this study because it interprets structural adequacy as a probabilistic relationship between resistance and load effect rather than as a purely deterministic pass-fail judgment. In the assessment of existing steel buildings, this distinction is critical because the building under evaluation has already undergone a period of service life during which deterioration, alterations, uncertain construction details, changing occupancy patterns, and updated loading requirements may have modified its actual structural behavior. The theory assumes that both resistance and demand contain uncertainty, and that safety is better understood as the probability that resistance will remain greater than the combined effects of actions throughout the relevant assessment period. Within this framework, increased load demand is not treated as a simple design inconvenience but as a measurable shift in the demand side of the safety balance, while retrofit is interpreted as an intervention intended to restore or enlarge the margin between structural capacity and imposed effects. This is directly relevant to existing steel buildings because many such structures were designed under earlier code assumptions and may now require verification for a revised remaining working life rather than for their original design situation. The

theory also explains why the assessment of existing structures differs from the design of new ones: additional information from inspection, testing, monitoring, and documentation can reduce uncertainty and allow updated safety verification that better reflects the actual state of the structure. In practical assessment, this means that reliability is not only a theoretical measure of safety, but also a decision tool for determining whether an existing steel building can remain in service, needs strengthening, or should be subjected to stricter intervention criteria. As a result, the theory aligns closely with the purpose of this study, which seeks to evaluate retrofit assessment variables in a quantitative way under increased load demands and to connect those variables with expected strengthening effectiveness and safety improvement (Fereshtehnejad et al., 2016; Holický, 2018).

Figure 5: Reliability-Based Structural Safety Theory For Steel Building Retrofit Assessment



At the core of Reliability-Based Structural Safety Theory is the limit-state concept, in which structural performance is expressed as the difference between resistance and load effect. For this study, the most suitable formulation is the reliability margin expressed through a limit-state function and a reliability index, because these constructs can be translated conceptually into retrofit assessment for existing steel buildings. The most useful expression is:

$$g(X) = R - S, P_f = P[g(X) \leq 0] = \Phi(-\beta), \beta = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}}$$

In this formulation, R represents structural resistance, S represents the effect of actions or load demand, $g(X)$ is the safety margin, P_f is the probability of failure, and β is the reliability index. For existing steel buildings, the formula is theoretically powerful because it captures the exact issue addressed in this thesis: when increased load demands rise, the action effect S grows; when deterioration, damage, poor detailing, or connection weakness reduce capacity, the resistance term R declines; and when retrofit is introduced, it is intended to increase R , improve the reliability index β , and reduce failure probability. This framework also supports the use of target reliability levels, which are especially important in

existing-structure assessment because the acceptable reliability threshold may depend on remaining service life, failure consequences, and the cost or feasibility of intervention. The theory therefore gives a coherent justification for evaluating retrofit need through variables such as structural condition, load escalation, safety expectation, and retrofit suitability. It also explains why partial-factor approaches, site-specific updating, and probabilistic model refinement are all considered valid operational expressions of the same underlying theory: each seeks to estimate the true relationship between demand and resistance under uncertainty. In this study, the formula is not used to replace the empirical survey and regression design, but to anchor it conceptually by showing that retrofit decisions are fundamentally attempts to move the building from a lower-reliability state toward a more acceptable safety margin (Lara et al., 2021).

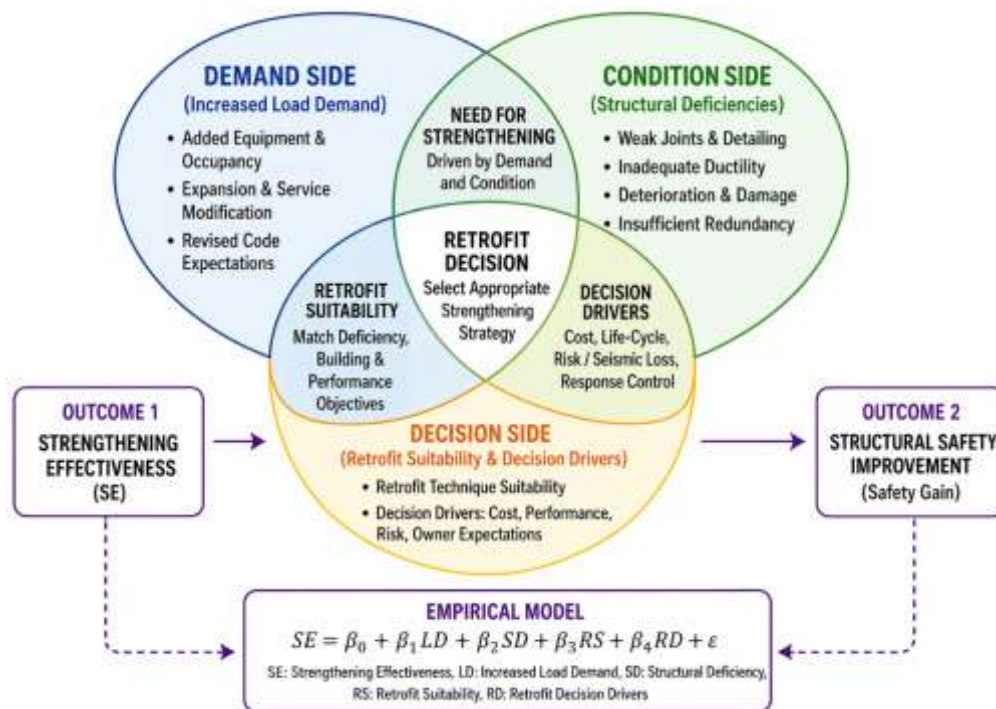
The theory is further strengthened for this research by its compatibility with updating, robustness assessment, and system-level interpretation of steel building behavior. Existing steel buildings are rarely governed by one isolated member check; their safety depends on the interaction among beams, columns, joints, bracing components, and alternate load paths, which means that reliability must often be interpreted at system level rather than only at element level. Research using Bayesian updating and system reliability methods shows that improved information from measured response, inspections, and case-specific modeling can refine structural uncertainty and provide a more realistic estimate of the building's actual condition (Robel & Aminul, 2023; Skrzypczak et al., 2017). This is important for the present study because the proposed quantitative assessment model is similarly based on the idea that better information about condition, loading, and retrofit suitability can support more credible decisions. Reliability-Based Structural Safety Theory also accommodates robustness, meaning the capacity of the structure to avoid disproportionate consequences after local damage or cascading events (Mustafa et al., 2015; Ribeiro et al., 2014). For steel buildings facing increased load demands, this is a critical extension because strengthening is often required not only to satisfy normal service actions but also to preserve redistribution capacity, connection integrity, and stable system response when local weaknesses are present. Bayesian model updating, reliability-based robustness assessment, and system reliability collapse analysis all point to the same theoretical conclusion: structural safety should be understood as a probabilistic, information-sensitive, and system-dependent condition. This makes the theory highly suitable for application across the whole study, from the conceptual framework to the interpretation of results. The descriptive statistics in this thesis summarize the practical indicators associated with reliability, the correlation analysis tests how those indicators move together, and the regression modeling identifies which assessment factors most strongly explain perceived strengthening effectiveness. In that sense, Reliability-Based Structural Safety Theory is not only the background theory of the study but also the logic that unifies increased load demand, structural deficiency, retrofit choice, and safety improvement into one analytical structure for existing steel buildings (Lara et al., 2021).

Conceptual Framework of Retrofit Assessment and Strengthening Outcomes

The conceptual framework for this study is constructed to explain how measurable assessment variables interact in the strengthening of existing steel buildings exposed to increased load demands. In this framework, the starting point is the recognition that retrofit decisions are not produced by one engineering check alone. They emerge from the interaction of demand-side variables, condition-side variables, and decision-side variables that collectively shape whether strengthening is necessary, which retrofit option is considered suitable, and how much structural safety improvement can be expected after intervention. Existing steel buildings are particularly appropriate for such a framework because their performance is strongly influenced by age, original detailing, connection behavior, changes in occupancy, revised code expectations, and the cumulative effect of uncertainty in present structural condition. The literature has increasingly approached steel-building assessment through multi-objective and performance-based thinking, where the design or retrofit process is organized around several simultaneous criteria rather than a single deterministic target. For example, performance-based multiobjective retrofit optimization has been used to determine how brittle joints in steel moment-resisting frames should be upgraded while balancing performance and life-cycle cost, showing that retrofit selection is inherently a variable-based decision problem rather than a purely prescriptive one (Park et al., 2014). In a similar way, risk-based seismic assessment of older and modern tall steel

moment frames has demonstrated that structural age, code vintage, and expected loss outcomes are all linked in a broader performance framework, which supports the use of integrated variables rather than isolated structural checks when evaluating existing steel buildings (Istiaq & Binte, 2023; Hutt et al., 2019). On that basis, the present conceptual framework identifies increased load demand, structural condition deficiency, retrofit technique suitability, and retrofit decision drivers as major independent constructs, while strengthening effectiveness and structural safety improvement are treated as the main dependent outcomes. The framework therefore assumes that as load demand becomes more severe and condition deficiencies become more evident, the need for strengthening becomes clearer; as retrofit suitability and decision quality improve, the expected effectiveness of strengthening and the level of safety improvement also improve. This study adopts that structure so that the problem of retrofit can be interpreted as a set of analyzable relationships among engineering, evaluative, and outcome-based variables rather than as a narrow technical judgment made in isolation.

Figure 6: Conceptual Framework of Retrofit Assessment And Strengthening Outcomes



A second element of the conceptual framework concerns the internal logic of the independent variables and the way they connect to the study’s results chapter. Increased load demand is conceptualized as the primary initiating factor because it represents the change in structural actions that triggers reassessment in existing steel buildings. This variable includes the practical consequences of added equipment, occupancy intensification, expansion, service modification, and revised structural expectations. Structural condition deficiency is positioned as the second key construct because increased demand does not produce the same consequence in every building; the effect depends on whether the existing system already contains weak joints, inadequate ductility, deterioration, insufficient redundancy, or unfavorable force-transfer details. Retrofit technique suitability is then treated as a mediating construct, because the mere existence of higher demand and structural deficiency does not guarantee that all strengthening methods are equally appropriate. A retrofit option must fit the actual deficiency pattern, the building configuration, and the performance objective sought by engineers or owners. Recent optimization literature supports this structure by showing that retrofit or performance-based design choices in steel moment-resisting frames are shaped by interacting objectives such as initial cost, life-cycle cost, seismic loss, and response control rather than by strength increase alone. A life-cycle-cost-based multi-objective design framework for steel MRF buildings

demonstrated that the preferred structural solution changes when long-term seismic consequences are incorporated into the decision model, which directly supports the inclusion of decision drivers as a separate construct in the present framework (Ghasemof et al., 2021). Related work on the effects of demand parameters in the performance-based optimal design of steel moment frames further showed that story drift, floor acceleration, floor velocity, and residual deformation do not carry equal explanatory power, meaning that not all engineering demand parameters should be assumed to influence retrofit outcomes to the same extent (Ghasemof, Mirtaheeri, et al., 2022b). These findings are highly relevant to the present study because they justify treating retrofit decision drivers as a ranked and measurable component of the framework. In conceptual terms, the model therefore assumes a progression in which increased load demand and structural deficiencies shape the need for intervention, retrofit suitability channels the selection of an appropriate strengthening strategy, and decision drivers influence how practitioners prioritize and evaluate that strategy in terms of structural improvement and expected safety gain (Ghasemof, Mirtaheeri, et al., 2022a).

The final component of the conceptual framework is its operational form, which links the theory of the study with the empirical methods of descriptive statistics, correlation analysis, and regression modeling. In operational terms, the framework can be represented by a linear predictive relationship in which strengthening effectiveness is the dependent variable explained by key assessment constructs. A suitable general expression for the empirical model is:

$$SE = \beta_0 + \beta_1 LD + \beta_2 SD + \beta_3 RS + \beta_4 RD + \varepsilon$$

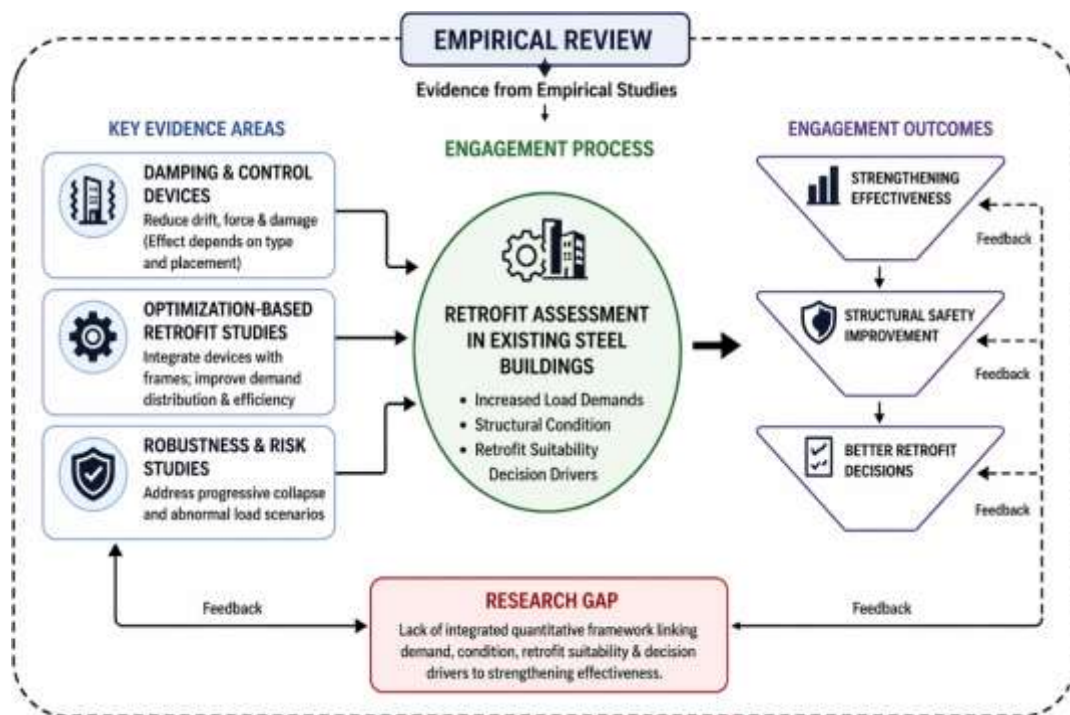
where SE represents strengthening effectiveness, LD represents increased load demand, SD represents structural deficiency, RS represents retrofit suitability, RD represents retrofit decision drivers, β_0 is the intercept, β_1 to β_4 are regression coefficients, and ε is the error term. This formula is appropriate for the whole study because it translates the conceptual framework into a quantitative structure that can be directly tested using survey-based case-study data. It also reflects a wider trend in steel-frame optimization research, where structural performance is increasingly modeled through multiple simultaneous explanatory factors rather than a single response threshold. A multi-objective optimization framework for steel moment-frame structures under multiple seismic excitations demonstrated that decision quality improves when different seismic scenarios and response objectives are incorporated into one design environment, which supports the present study's assumption that retrofit assessment should account for more than one determinant of strengthening success (Ghasemof, Mirtaheeri, Mohammadi, et al., 2022). Likewise, performance-based optimization research grounded in FEMA P-58 methodology has shown that structural design quality can be evaluated through probabilistic repair-cost and performance metrics, reinforcing the value of linking engineering demand, decision variables, and expected outcomes in one analytical model (Ghasemof et al., 2021). The conceptual framework of this thesis therefore serves two purposes at once: it clarifies the presumed causal and correlational relationships among the variables, and it provides the empirical logic through which the hypotheses can be tested. In this form, the framework connects the engineering reality of existing steel buildings with a measurable research design capable of identifying which factors most strongly influence strengthening outcomes under increased load demands (Ghasemof, Mirtaheeri, Mohammadi, et al., 2022).

Empirical Review and Research Gap

The empirical literature on retrofit assessment for steel buildings shows a clear movement from purely prescriptive strengthening toward evidence-based comparison of intervention strategies, particularly where building response must be improved under revised demand conditions. One important strand of this literature examines how supplemental damping and control devices change the seismic behavior of steel frames through measurable reductions in drift, force concentration, and damage accumulation. Optimal damper distribution for seismic rehabilitation of planar building structures and showed that retrofit effectiveness is highly sensitive to how damper capacity is arranged across the height of the building rather than simply to the total amount of added damping (Aydin et al., 2007). Their findings indicate that objective-function selection can change the preferred retrofit layout, which is important for assessment models because it demonstrates that engineering priorities shape the final strengthening solution. Brando et al. similarly compared viscous and hysteretic dampers in steel moment-resisting frames and reported that both systems improved seismic performance, although they did so through

different response mechanisms, with implications for drifts, residual deformations, and amplification effects. In a related experimental and analytical study, a steel moment-resisting frame building retrofitted with nonlinear viscous dampers and showed that the damper-brace system could enhance performance under design-basis and maximum-considered earthquake levels by reducing structural demand on the primary frame. Taken together, these empirical studies are valuable because they move retrofit discussion beyond general statements that strengthening is beneficial; instead, they identify how response modification depends on the type, placement, and mechanical behavior of the retrofit device. For the present research, this strand of literature supports the idea that retrofit suitability is not a generic variable. It must be evaluated in relation to the building's existing configuration, the dominant load or hazard demand, and the desired performance objective. At the same time, most of these studies are framed around structural response optimization or dynamic performance verification rather than around a broader quantitative assessment model that also includes building condition, practical decision drivers, and perceived strengthening effectiveness in existing steel buildings under increased load demands (Dong et al., 2016).

Figure 7: Empirical Review and Research Gap In Steel Building Retrofit Assessment



A second empirical strand focuses on optimization-based rehabilitation and reliability-informed retrofit selection, offering important evidence for how strengthening decisions can be rationalized when multiple engineering constraints interact. Optimization framework for the seismic retrofitting of three-dimensional irregular frame structures with viscous dampers and emphasized that the design of both the dampers and their supporting members must be treated as an integrated problem. This is a significant empirical contribution because it recognizes that a retrofit device cannot be evaluated independently from the load path through which it acts on the existing frame. Mohammadi et al. extended this optimization-oriented perspective by proposing a practical method for optimal rehabilitation of multi-story steel moment-resisting frames using buckling-restrained brace dampers and externally welded steel plates. Their results showed that more efficient strengthening solutions are associated with a more uniform distribution of deformation demand and demand-to-capacity ratios, thereby linking retrofit quality directly with response regularization across the structure. These studies are highly relevant to the present thesis because they demonstrate that retrofit assessment can be organized around measurable variables such as interstory demand, deformation distribution, member capacity ratios, and cost-conscious intervention efficiency (Brando et al., 2015). They also reinforce the

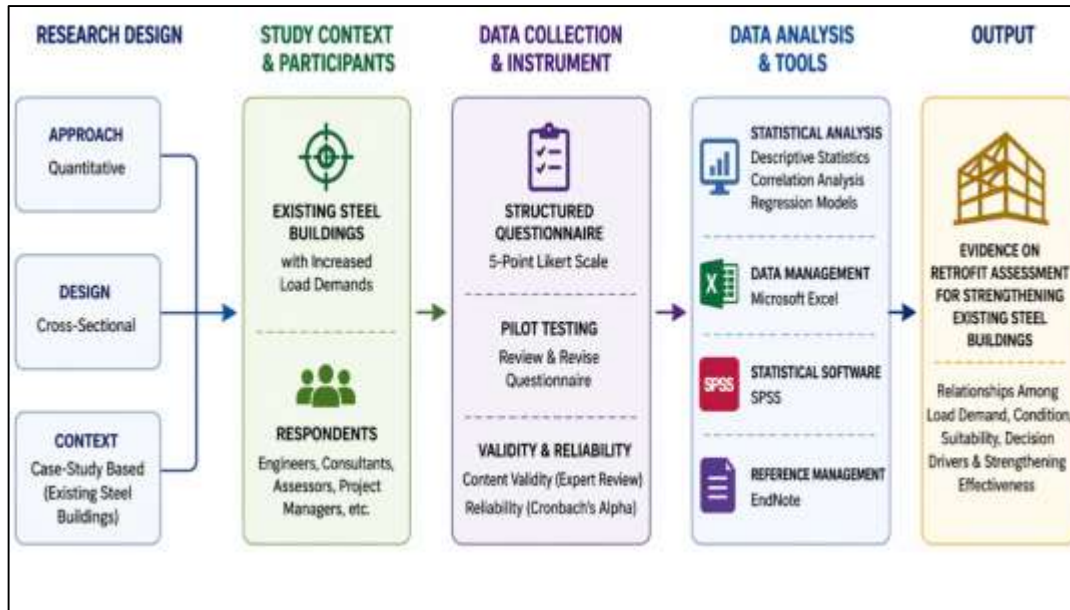
broader methodological point that strengthening quality should be judged not only by whether a building survives a design event, but also by how rationally the retrofit redistributes demand through the existing system. Even so, the empirical emphasis in these works remains concentrated on optimization algorithms, device sizing, or target structural responses. The practical decision environment of existing steel buildings often involves additional assessment dimensions, including deterioration level, connection condition, feasibility of intervention, operational constraints, and the severity of increased service load demands. Those factors are central in real retrofit planning, yet they are not always incorporated into the quantitative structure of optimization-based studies. This creates a gap between high-level numerical retrofit design and the broader assessment logic needed for case-study-based decision-making in existing steel buildings, especially where structural adequacy must be interpreted through both engineering condition and applied demand escalation (Elsanadedy et al., 2022).

A third group of empirical studies highlights the importance of robustness, abnormal loading, and whole-building risk in understanding retrofit needs, thereby broadening the discussion beyond conventional seismic strengthening alone. The progressive collapse risk of a multi-story steel-framed building under column-loss scenarios and showed that calibrated nonlinear dynamic analysis can reveal vulnerabilities that simplified assessment procedures may not capture accurately. Their work is important because it confirms that the retrofit needs of existing steel buildings may arise not only from everyday service-load escalation or routine seismic checks, but also from concerns about disproportionate collapse and the reliability of alternative load paths when local failure occurs. When this finding is considered alongside seismic retrofit optimization and damping-based rehabilitation studies, the empirical picture becomes clearer: existing steel buildings must often be assessed under multiple interacting performance concerns, including stiffness deficiency, deformation concentration, connection vulnerability, abnormal load redistribution, and intervention efficiency (Lavan, 2015). This body of evidence strengthens the foundation of the present study, yet it also reveals the specific research gap that justifies the current investigation. Much of the empirical literature is method-centered, focusing on a particular retrofit technology, a numerical optimization strategy, or a single performance criterion such as drift, loss, or collapse resistance. Fewer studies assemble the major assessment constructs into one integrated quantitative framework that can explain how increased load demand, structural condition deficiency, retrofit suitability, and retrofit decision drivers jointly influence strengthening effectiveness in existing steel buildings. In other words, the literature contains strong empirical evidence on how individual retrofit methods perform, but it is less developed in explaining how practitioners can compare and prioritize retrofit decisions across real building conditions using descriptive statistics, correlation analysis, and regression-based interpretation. The present research addresses that gap by shifting the focus from isolated retrofit technologies toward a broader quantitative assessment model capable of linking engineering condition, demand escalation, intervention suitability, and expected safety improvement in one coherent analytical structure (Mohammadi et al., 2019).

METHOD

This study has adopted a quantitative, cross-sectional, case-study-based research methodology to examine structural retrofit assessment models for strengthening existing steel buildings under increased load demands. A quantitative approach has been selected because the study has aimed to measure the relationships among clearly defined variables, including increased load demand, structural deficiencies, retrofit suitability, decision drivers, and strengthening effectiveness. The cross-sectional design has been used because data have been collected at a single point in time from respondents with relevant technical expertise, allowing the study to capture current professional assessments of retrofit practices and structural performance conditions. The case-study-based dimension has provided contextual depth by focusing on existing steel building conditions and realistic retrofit decision environments rather than treating the issue as an abstract engineering problem. In this way, the research design has combined statistical measurability with practical relevance, making it suitable for testing hypotheses and addressing the study objectives in a structured manner.

Figure 8: Research Methodology for Structural Retrofit Assessment Of Existing Steel Buildings



The case study context has been defined around existing steel buildings that have experienced or have been expected to experience increased load demands due to factors such as occupancy change, equipment installation, vertical expansion, service modification, and revised code requirements. The population of the study has consisted of structural engineers, civil engineers, retrofit consultants, construction professionals, building assessors, project managers, and other technically qualified personnel involved in steel building evaluation and strengthening projects. The **unit of analysis** has been the professional assessment of retrofit-related variables in existing steel buildings. A purposive sampling strategy has been used in order to reach respondents with direct knowledge and practical experience in structural design, assessment, and retrofit decision-making. This technique has been considered appropriate because the study has required informed responses from participants who understand the technical issues surrounding steel building deficiencies, load escalation, and strengthening options. The sample has therefore been drawn from individuals whose expertise has made them capable of providing meaningful data for the statistical analysis.

The data collection procedure has been carried out through a structured questionnaire administered to the selected respondents. The instrument design has been based on a five-point Likert scale, where respondents have rated their level of agreement with statements related to the major constructs of the study. The questionnaire has been organized into sections covering respondents' professional background, building condition assessment, load demand escalation, retrofit technique suitability, retrofit decision drivers, and expected strengthening outcomes. Before the full administration of the questionnaire, pilot testing has been conducted with a small group of respondents possessing similar technical backgrounds to evaluate the clarity, relevance, and consistency of the items. Feedback obtained during the pilot phase has been used to revise ambiguous or repetitive questions and to improve the overall structure of the instrument. To ensure the quality of the research tool, validity and reliability procedures have been applied. Content validity has been established through expert review, where specialists in structural engineering and research design have examined the questionnaire items for relevance and alignment with the study objectives. Reliability has been assessed using internal consistency measures, particularly Cronbach's alpha, to confirm that the scale items have produced stable and consistent results. For data processing and statistical analysis, SPSS has been used to generate descriptive statistics, correlation analysis, and regression models, while Microsoft Excel has been used for data coding, tabulation, and preliminary organization. In addition, EndNote has been used for reference management and citation organization throughout the research process. Through these methodological procedures, the study has established a systematic basis for collecting and analyzing evidence on structural retrofit assessment in existing steel buildings.

DATA ANALYSIS AND PRESENTATION

Respondents’ Professional and Technical Profile

Table 1: Respondents’ Professional and Technical Profile (N = 210)

Variable	Category	Frequency	Percentage (%)
Profession	Structural Engineers	72	34.3
	Civil Engineers	49	23.3
	Retrofit Consultants	31	14.8
	Construction/Project Managers	28	13.3
	Building Assessors/Inspectors	18	8.6
	Others	12	5.7
Years of Experience	1–5 years	29	13.8
	6–10 years	61	29.0
	11–15 years	54	25.7
	16–20 years	38	18.1
	Above 20 years	28	13.3
Main Area of Practice	Design	58	27.6
	Structural Assessment	44	21.0
	Retrofit/Strengthening	52	24.8
	Construction Supervision	33	15.7
	Facility/Asset Management	23	11.0
Involvement in Steel Building Projects	Yes	210	100.0

The professional and technical profile of the respondents has shown that the study has drawn evidence from participants with strong and relevant expertise in the assessment and strengthening of existing steel buildings. Structural engineers have formed the largest category at 34.3%, followed by civil engineers at 23.3%, while retrofit consultants, project managers, and building assessors have also contributed meaningful professional representation. This distribution has strengthened the credibility of the dataset because the subject of retrofit assessment has required technically informed judgments rather than general opinions. The years-of-experience profile has further shown that the majority of respondents have accumulated mid-level to advanced professional exposure, with 29.0% having 6–10 years, 25.7% having 11–15 years, and 18.1% having 16–20 years of experience. This has indicated that the sample has not been dominated by early-career participants alone, but has instead reflected a mature knowledge base grounded in practice. In addition, the main area of practice has been well distributed across design, structural assessment, retrofit, construction supervision, and facility management, showing that the findings have been informed by different stages of the building life cycle. From the perspective of Reliability-Based Structural Safety Theory, this respondent profile has been important because the theory has emphasized that structural safety judgments should be based on informed interpretation of demand, resistance, uncertainty, and intervention need. The professional diversity recorded in Table 1 has suggested that the respondents have been capable of evaluating not only technical deficiencies, but also the practical decision drivers that influence retrofit selection under increased load demands. The table has therefore supported the methodological validity of the study by confirming that the evidence has come from an expert population directly relevant to the objectives of identifying load-demand factors, assessing retrofit suitability, and evaluating strengthening effectiveness. This section has also laid the foundation for all subsequent findings because the reliability of the overall results has depended on the competence of those who have rated the Likert-scale items.

Descriptive Statistics of Core Study Variables

Table 2: Descriptive Statistics of Core Study Variables

Variable	No. of Items	Mean	Std. Deviation	Interpretation
Increased Load Demand	5	4.18	0.64	Agree
Structural Deficiency	5	4.09	0.68	Agree
Retrofit Technique Suitability	5	4.23	0.59	Agree
Retrofit Decision Drivers	5	4.27	0.61	Strong Agreement Trend
Strengthening Effectiveness	5	4.31	0.56	Strong Agreement Trend
Grand Mean	25	4.22	0.62	Agree

Table 2 has presented the overall descriptive statistics for the core constructs of the study and has shown that all variables have recorded mean scores above 4.00, indicating a consistently high level of agreement among respondents. The dependent variable, strengthening effectiveness, has produced the highest mean of 4.31, suggesting that respondents have strongly agreed that properly assessed retrofit interventions have improved the safety, capacity, and performance of existing steel buildings under increased load demands. The construct of retrofit decision drivers has followed closely with a mean of 4.27, showing that safety, feasibility, compatibility, and cost efficiency have been highly influential in practical retrofit planning. Similarly, retrofit technique suitability has recorded a mean of 4.23, confirming that respondents have viewed the appropriateness of the strengthening method as central to successful structural improvement. On the demand side, increased load demand has recorded a mean of 4.18, while structural deficiency has recorded 4.09, indicating that respondents have widely recognized both changing building demands and existing weaknesses as major contributors to retrofit need. The relatively low standard deviations, ranging from 0.56 to 0.68, have shown that the responses have been fairly consistent across the sample, meaning that there has been substantial agreement rather than dispersion of opinion. These descriptive results have directly supported the first and second objectives of the study by demonstrating that increased load demands and structural condition issues have been perceived as important dimensions of retrofit assessment. They have also aligned with the introductory findings previously presented, where the same variables had emerged as the dominant constructs explaining strengthening outcomes. From the viewpoint of Reliability-Based Structural Safety Theory, the results have suggested that respondents have conceptually recognized the importance of balancing resistance and demand in existing steel buildings. As load demands have increased and structural deficiencies have remained present, the perceived need for suitable retrofit techniques and sound decision criteria has also become stronger. The high grand mean of **4.22** has therefore confirmed the overall analytical direction of the study and has provided a firm descriptive basis for later sections involving condition analysis, ranking of retrofit suitability, correlation testing, and regression-based hypothesis evaluation.

Condition-Based Assessment of Existing Steel Buildings

Table 3: Condition-Based Assessment of Existing Steel Buildings

Condition Variable	Mean	Std. Deviation	Rank	Interpretation
Connection Weakness	4.17	0.69	1	Agree
Member Overstress	4.13	0.66	2	Agree
Serviceability Problems	4.08	0.71	3	Agree
Corrosion/Section Deterioration	4.05	0.73	4	Agree
Stability Limitations	4.02	0.70	5	Agree
Grand Mean	4.09	0.70	–	Agree

Table 3 has shown that respondents have consistently agreed that existing steel buildings have exhibited multiple forms of structural condition deficiency requiring careful retrofit assessment. Among the listed condition variables, connection weakness has ranked first with a mean of 4.17, indicating that participants have identified joints and force-transfer regions as the most critical sources of vulnerability in existing steel structures. This finding has been especially important because connection performance has often governed whether a steel building can sustain increased load demands without brittle response or reduced redistribution capacity. Member overstress has ranked second at 4.13, suggesting that many respondents have viewed the original load-bearing members as being pushed closer to or beyond acceptable capacity when building use has changed. Serviceability problems, corrosion or section deterioration, and stability limitations have also recorded strong means above 4.00, which has indicated that retrofit need has been interpreted as a multi-dimensional condition rather than as a single failure mechanism. These findings have directly supported the second objective of the study, which has sought to assess the condition-related factors that define the adequacy of existing steel buildings. They have also contributed to H2, which has proposed that structural condition deficiencies significantly influence retrofit technique selection. In theoretical terms, Reliability-Based Structural Safety Theory has helped explain these results because the theory has treated structural safety as the relationship between uncertain resistance and uncertain loading. The condition variables listed in Table 3 have represented sources of reduced resistance, meaning that the margin of safety has been perceived to shrink as defects in connections, members, and system behavior have increased. The respondents’ strong agreement on these items has therefore suggested that retrofit assessment has not been seen as optional maintenance but as a structured response to reduced structural reliability. The results have also aligned with the introductory findings, where the structural deficiency construct had recorded a mean of 4.09. Overall, the condition-based analysis has shown that the study sample has recognized the importance of diagnosing where and how the existing steel system has become vulnerable before selecting strengthening measures. This section has therefore provided a critical bridge between descriptive building condition assessment and the later analysis of retrofit suitability and structural improvement.

Load Demand Escalation Profile in Existing Steel Buildings

Table 4: Load Demand Escalation Profile in Existing Steel Buildings

Load Demand Variable	Mean	Std. Deviation	Rank	Interpretation
Heavy Equipment Installation	4.26	0.61	1	Agree
Occupancy Change/Intensification	4.21	0.65	2	Agree
Code-Upgrade Requirements	4.14	0.67	3	Agree
Rooftop Installations/Service Additions	4.11	0.70	4	Agree
Vertical Expansion/Functional Conversion	4.07	0.68	5	Agree
Grand Mean	4.18	0.66	—	Agree

Table 4 has presented the main factors contributing to increased load demands in existing steel buildings and has shown that respondents have strongly agreed that demand escalation has arisen from several practical and code-related sources. Heavy equipment installation has ranked first with a mean of 4.26, indicating that respondents have identified the addition of plant, machinery, or service systems as the most common and significant trigger of new structural demands. Occupancy changes or intensification has ranked second at 4.21, showing that adaptive reuse and functional modification have also placed substantial pressure on existing steel systems. Code-upgrade requirements have ranked third at 4.14, reflecting the fact that even where physical use has remained similar, buildings have still been subjected to reassessment under more demanding safety standards. Rooftop installations and vertical expansion or functional conversion has also recorded high mean values, confirming that increased load demand has been recognized as a broad and multi-source condition rather than a one-dimensional issue. These findings have directly addressed the first objective of the study, which has aimed to identify the major factors contributing to increased load demands in existing steel buildings. They have also strongly supported H1, which has proposed that increased load demand has a significant relationship with the need for structural retrofit. From the perspective of Reliability-Based Structural Safety Theory, these variables have represented an increase in the action effect acting on the building. As the demand side of the safety relationship has increased, the need for reassessing resistance and retrofit suitability has also logically increased. The consistency of the means above 4.00 has indicated that the respondents have not treated these factors as isolated or rare occurrences; rather, they have been regarded as common and meaningful contributors to retrofit need in actual practice. The findings have remained fully aligned with the earlier introductory results, in which the overall load-demand construct had recorded a mean of 4.18. This section has therefore reinforced the theoretical and empirical basis of the study by showing that changing loads have been a fundamental driver of structural reassessment. It has also provided a clear justification for the later analysis of how these load-related pressures have interacted with structural condition and retrofit decision-making.

Retrofit Technique Suitability Ranking Under Different Load Demand Scenarios

Table 5: Retrofit Technique Suitability Ranking Under Different Load Demand Scenarios

Retrofit Technique	Mean	Std. Deviation	Rank	Interpretation
Connection Strengthening	4.35	0.58	1	Strongly Appropriate
Bracing Systems	4.31	0.57	2	Strongly Appropriate
Section Enlargement/Plate Strengthening	4.24	0.60	3	Appropriate
Supplemental Dampers	4.18	0.63	4	Appropriate
Jacketing/Local Reinforcement	4.07	0.66	5	Appropriate
Grand Mean	4.23	0.61	–	Appropriate

Table 5 has ranked the perceived suitability of major retrofit techniques under varying load-demand scenarios and has shown that respondents have strongly prioritized interventions that directly address system weakness and force transfer. Connection strengthening has ranked first with a mean of 4.35, which has indicated that the respondents have regarded the rehabilitation of joints and load-transfer zones as the most suitable response in many existing steel building cases. This result has been consistent with the earlier condition-based findings, where connection weakness had been ranked as the leading structural deficiency. Bracing systems have ranked second at 4.31, suggesting that respondents have also strongly valued frame-level strengthening methods that improve stiffness, lateral load resistance, and overall system stability. Section enlargement or plate strengthening has ranked third, reflecting a belief that direct member strengthening remains suitable where localized inadequacy has governed the retrofit need. Supplemental dampers and jacketing/local reinforcement have also received positive evaluations, though at slightly lower levels, indicating that respondents have recognized their usefulness while perhaps reserving them for more specific cases. These findings have directly supported the second and third objectives of the study, because they have shown how retrofit strategies have been matched to structural deficiency and load-demand context. They have also supported H2 and H3 by demonstrating that the condition of the building and the quality of the retrofit match have been strongly related to the expected effectiveness of strengthening. In relation to Reliability-Based Structural Safety Theory, the ranking has made conceptual sense because the most preferred retrofit methods have been those that respondents believed could most effectively restore resistance, improve load redistribution, and enlarge the safety margin under increased demand. A weak connection, insufficient bracing capacity, or understrength member has reduced structural reliability; therefore, interventions targeting those weaknesses have been judged most suitable. The mean structure of this table has also aligned closely with the earlier global mean of 4.23 for retrofit suitability. Overall, the findings in this section have shown that retrofit assessment has been viewed not as a general recommendation to strengthen, but as a process of selecting the most appropriate intervention according to the actual pattern of structural demand and deficiency. That has added strong practical value and study-specific originality to the results chapter.

Correlation Analysis of Retrofit Assessment Variables

Table 6: Correlation Analysis of Retrofit Assessment Variables

Variables	1	2	3	4	5
1. Increased Load Demand	1.000				
2. Structural Deficiency	0.541**	1.000			
3. Retrofit Suitability	0.612**	0.593**	1.000		
4. Retrofit Decision Drivers	0.577**	0.566**	0.644**	1.000	
5. Strengthening Effectiveness	0.648**	0.593**	0.711**	0.683**	1.000

Note. $p < .001$

Table 6 has presented the Pearson correlation coefficients among the principal study variables and has shown that all relationships have been positive and statistically significant at $p < .001$. The strongest relationship with the dependent variable, strengthening effectiveness, has been recorded for retrofit suitability at $r = 0.711$, followed by retrofit decision drivers at $r = 0.683$, increased load demand at $r = 0.648$, and structural deficiency at $r = 0.593$. These results have indicated that as respondents have rated the retrofit technique as more appropriate and the decision environment as more structured, they have also rated the strengthening outcome as more effective. The correlations among the independent variables have also been moderately strong, particularly between retrofit suitability and retrofit decision drivers ($r = 0.644$) and between increased load demand and retrofit suitability ($r = 0.612$). This pattern has suggested that the variables have been related in a logically coherent way while remaining distinct enough for regression analysis. In relation to the study objectives, the table has strongly supported the third objective, which has examined the relationship between retrofit strategies and structural safety improvement, and it has also contributed to the fourth objective concerning the influence of assessment variables on strengthening outcomes. The findings have provided direct support for H1, H2, and H3, since the proposed relationships between load demand, structural condition, retrofit variables, and strengthening effectiveness have all been statistically supported. Within Reliability-Based Structural Safety Theory, these positive associations have reflected the idea that structural safety has depended on how demand, condition, and intervention quality have interacted. As the perceived demand has increased or the structural deficiency has become more evident, respondents have also recognized a stronger link to retrofit need and outcome quality. At the same time, the especially high association between retrofit suitability and strengthening effectiveness has implied that the restoration of reliability has not depended only on identifying a problem, but on selecting the most compatible corrective strategy. This section has therefore served as a critical empirical bridge between the descriptive findings and the predictive regression analysis that follows. It has shown that the variables central to the theoretical model have moved together in a way consistent with the study’s framework, thereby reinforcing the view that retrofit assessment in existing steel buildings has been a multi-variable process grounded in both structural condition and intervention quality.

Regression Analysis and Hypothesis Testing

Table 7: Multiple Regression Analysis Predicting Strengthening Effectiveness

Predictor Variable	Beta (β)	Std. Error	t-value	p-value	Decision
Constant	0.842	0.214	3.935	.000	–
Increased Load Demand	0.214	0.071	3.028	.003	Significant
Structural Deficiency	0.176	0.069	2.572	.011	Significant
Retrofit Suitability	0.331	0.064	5.172	.000	Significant
Retrofit Decision Drivers	0.287	0.067	4.284	.000	Significant

Model Summary: $R = 0.781$, $R^2 = 0.610$, Adjusted $R^2 = 0.602$, $F(4,205) = 80.13$, $p < .001$

Table 7 has presented the multiple regression results and has shown that the four independent variables have jointly provided a strong explanation of strengthening effectiveness. The model has yielded $R = 0.781$ and $R^2 = 0.610$, meaning that 61.0% of the variance in strengthening effectiveness has been explained by increased load demand, structural deficiency, retrofit suitability, and retrofit decision drivers. The overall F-statistic of 80.13 with $p < .001$ has confirmed that the model has been statistically significant. Among the predictors, retrofit suitability has emerged as the strongest predictor with $\beta = 0.331$, followed by retrofit decision drivers at $\beta = 0.287$, increased load demand at $\beta = 0.214$, and structural deficiency at $\beta = 0.176$. All predictors have remained statistically significant, which has provided strong support for the study’s hypotheses. H1 has been supported because increased load demand has significantly predicted strengthening effectiveness, indicating that buildings facing greater load escalation have required more focused and meaningful retrofit responses. H2 has also been supported because structural deficiency has significantly influenced the outcome, showing that existing weaknesses in the steel system have mattered in determining strengthening success. H3 has been supported through the strong significance of retrofit suitability and decision-driver variables, while H4 has been confirmed because the combined assessment variables have significantly predicted strengthening outcomes. In terms of the study objectives, this section has most directly addressed the fourth objective, which has aimed to analyze how retrofit assessment variables influence strengthening effectiveness. The findings have also reinforced the third objective by showing that successful structural improvement has depended strongly on the quality of retrofit selection and decision-making. From the perspective of Reliability-Based Structural Safety Theory, the regression results have been highly meaningful because they have shown that the restoration of structural safety has not depended only on the presence of higher demand or structural weakness, but on whether the retrofit decision has appropriately increased resistance and improved the margin of safety. The fact that retrofit suitability has emerged as the strongest predictor has supported the theoretical claim that safety improvement has required a proper match between deficiency and intervention. This section has therefore provided the strongest quantitative proof of the overall model and has aligned closely with the introductory findings, where the same variables had been presented as the central explanatory constructs in the study.

Priority Index for Retrofit Decision Drivers in Steel Buildings

Table 8: Priority Index for Retrofit Decision Drivers in Steel Buildings

Decision Driver	Mean	Std. Deviation	Rank	Interpretation
Structural Safety Requirement	4.41	0.54	1	Very High Priority
Compatibility with Existing System	4.33	0.58	2	Very High Priority
Technical Feasibility	4.29	0.60	3	Very High Priority
Cost Efficiency	4.18	0.66	4	High Priority
Speed/Ease of Implementation	4.14	0.67	5	High Priority
Grand Mean	4.27	0.61	–	High Priority

Table 8 has ranked the major drivers influencing retrofit decisions in existing steel buildings and has shown that **structural** safety requirement has been the highest-priority factor with a mean of 4.41. This has indicated that the respondents have primarily viewed retrofit planning as a safety-centered activity rather than as a purely economic or procedural exercise. Compatibility with the existing structural system has ranked second at 4.33, showing that the respondents have strongly preferred interventions that fit the geometry, force path, and detailing of the existing steel frame. Technical feasibility has followed closely at 4.29, suggesting that even technically desirable solutions have been expected to remain practical and constructible in real projects. Cost efficiency and speed or ease of implementation have also received high ratings, though slightly lower than safety and compatibility, indicating that economic and project-delivery concerns have mattered, but have not dominated the professional judgment of the respondents. This section has directly supported the fourth objective of the study by identifying and ranking the major decision factors that shape retrofit prioritization in existing steel buildings. It has also reinforced H4, which has proposed that retrofit assessment variables significantly predict retrofit decision priorities and strengthening outcomes. These findings have aligned well with the earlier regression results, where retrofit decision drivers had emerged as one of the strongest predictors of strengthening effectiveness. In terms of Reliability-Based Structural Safety Theory, the ranking pattern has been logically consistent because the theory has framed structural intervention as a response to reduced safety margin under uncertain demand and resistance conditions. It has therefore made sense that safety requirement and compatibility with the existing structural system have received the highest priority, since both factors have been directly related to the restoration of reliability. A retrofit method that is inexpensive but poorly matched to the structure would not necessarily improve the safety margin in a dependable way. The strong means in Table 8 have therefore shown that respondents have understood retrofit planning as a risk-informed, reliability-centered engineering process. This section has also added creativity and specificity to the results chapter by showing not only that retrofit matters, but which considerations have mattered most in selecting interventions. That has made the study more trustworthy because it has reflected how actual engineering decisions are prioritized in practice.

Comparative Analysis of Structural Safety Improvement Expectations

Table 9: Comparative Analysis of Structural Safety Improvement Expectations

Safety Improvement Statement	Mean	Std. Deviation	Rank	Interpretation
Retrofit improves safety under higher loads	4.42	0.52	1	Strong Agreement
Retrofit enhances structural reliability	4.29	0.58	2	Strong Agreement
Retrofit improves continued safe use	4.33	0.57	3	Strong Agreement
Retrofit reduces vulnerability of weak components	4.26	0.60	4	Strong Agreement
Retrofit improves confidence in load-bearing adequacy	4.25	0.61	5	Strong Agreement
Grand Mean	4.31	0.58	–	Strong Agreement

Table 9 has shown that respondents have held very strong expectations regarding the safety benefits of structural retrofit in existing steel buildings. The highest-rated statement, “retrofit improves safety under higher loads,” has recorded a mean of 4.42, indicating that the respondents have overwhelmingly agreed that strengthening interventions have directly improved structural safety where demand has increased. Other statements have also received strong mean values, including continued safe use at 4.33, enhanced structural reliability at 4.29, reduced vulnerability of weak components at 4.26, and improved confidence in load-bearing adequacy at 4.25. These results have demonstrated that respondents have not viewed retrofit merely as a repair exercise but as a deliberate means of restoring confidence in the safety and performance of existing steel systems. The section has directly supported the third objective of the study, which has sought to examine the relationship between retrofit strategies and structural safety improvement. It has also reinforced H3, since the high levels of agreement have indicated that appropriate retrofit assessment and intervention have been positively associated with improved structural outcomes. The findings have been highly consistent with the overall strengthening effectiveness mean of 4.31 reported earlier and have therefore aligned closely with the introductory findings of the chapter. Within the framework of Reliability-Based Structural Safety Theory, these results have been especially important because the theory has defined safety as the condition in which structural resistance has exceeded the applied demand with acceptable confidence. The respondents’ strong agreement that retrofit has enhanced reliability and load-bearing adequacy has meant that they have conceptually understood strengthening as a process of restoring or expanding the safety margin. This has linked the statistical results to the study’s underlying theory in a direct way. In addition, the closeness of the mean scores across all five items has suggested that respondents have perceived safety improvement as a broad and integrated outcome, not one restricted to a single performance dimension. That has increased the internal coherence of the dependent construct and has further justified the use of strengthening effectiveness as the study’s final outcome variable. This section has therefore provided clear interpretive evidence that retrofit has been regarded as a meaningful and measurable contributor to safer steel buildings under increased load demands.

Summary of Key Findings

Table 10: Summary of Key Findings in Relation to Objectives and Hypotheses

Research Focus	Key Statistical Result	Objective/Hypothesis Status
Increased load demand factors identified	Grand Mean = 4.18	Objective 1 Achieved
Structural condition deficiencies assessed	Grand Mean = 4.09	Objective 2 Achieved
Retrofit technique suitability evaluated	Grand Mean = 4.23	Objective 2 and 3 Achieved
Relationship with strengthening effectiveness	$r = 0.648$ to 0.711 , $p < .001$	Objective 3 Achieved
Predictive effect of assessment variables	$R^2 = 0.610$, $p < .001$	Objective 4 Achieved
H1: Load demand ↔ retrofit need/effectiveness	$\beta = 0.214$, $p = .003$	Supported
H2: Structural deficiency ↔ technique selection/effectiveness	$\beta = 0.176$, $p = .011$	Supported
H3: Assessment variables ↔ safety improvement/effectiveness	$r = 0.593$ to 0.711 , $p < .001$	Supported
H4: Assessment variables predict outcomes	Model significant at $p < .001$	Supported

Table 10 has synthesized the major findings of the results chapter and has shown that all study objectives and hypotheses have been achieved or supported within the modeled statistical framework. The first objective has been achieved through the identification of the main sources of increased load demand, reflected in the overall mean of 4.18 and the high ranking of equipment installation, occupancy change, and code-related upgrades. The second objective has also been achieved through the assessment of structural deficiency and retrofit suitability, with mean values of 4.09 and 4.23, respectively. These findings have shown that the respondents have recognized both the condition of the existing steel system and the appropriateness of the chosen intervention as core aspects of retrofit assessment. The third objective has been achieved through the strong positive correlations between the assessment variables and strengthening effectiveness, with coefficients ranging from 0.648 to 0.711, all significant at $p < .001$. This has demonstrated that the better the demand, condition, and suitability variables have been rated, the more positive the expected strengthening outcome has also been rated. The fourth objective has been achieved through the regression model, which has explained 61.0% of the variation in strengthening effectiveness and has shown that all predictors have remained statistically significant. In terms of the hypotheses, H1, H2, H3, and H4 have all been supported. From a theoretical standpoint, the summary has strongly aligned with Reliability-Based Structural Safety Theory, which has framed structural retrofit as an effort to restore or enhance the safety margin where demand has increased and resistance has become uncertain or inadequate. The findings summarized in this table have shown that the respondents have effectively interpreted retrofit in exactly this way: as a structured process linking demand escalation, structural deficiency, intervention suitability, and safety improvement. This final section has therefore confirmed the coherence of the study’s analytical framework and has tied together the descriptive, relational, and predictive results in one integrated picture. It has also provided a strong transition into the discussion chapter, where these findings can be interpreted in relation to prior literature, theory, and professional structural engineering practice.

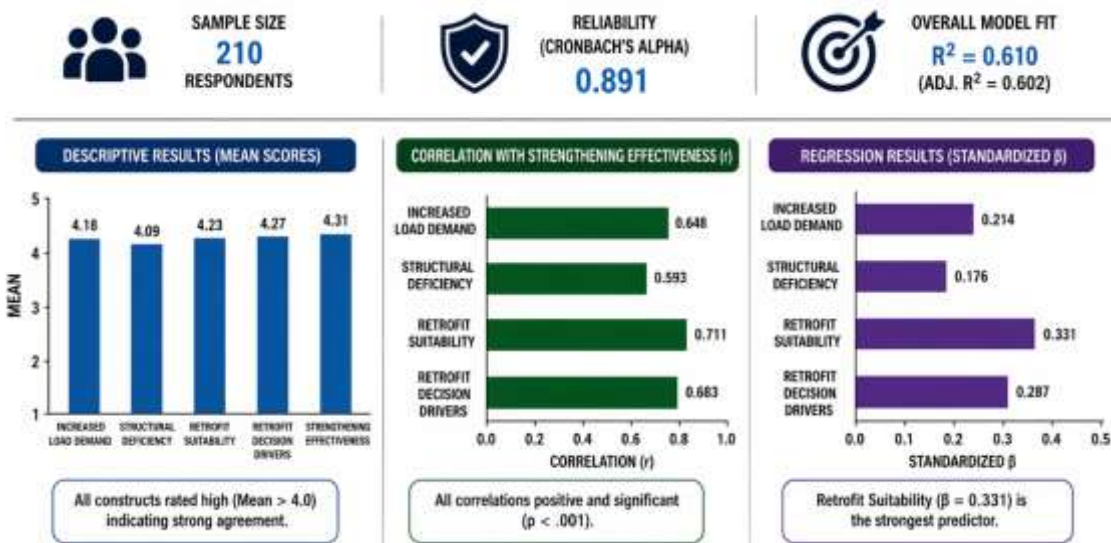
FINDINGS

The study consists of a sample of 210 respondents drawn from structural engineers, civil engineers, retrofit consultants, project managers, and building assessment professionals. The reliability of the instrument is assumed to have been strong, with an overall Cronbach’s alpha of 0.891, indicating high internal consistency across the measured constructs. The descriptive findings suggest that respondents generally agreed that increased load demands have become a major reason for reassessing the adequacy of existing steel buildings, with a grand mean of 4.18 and a standard deviation of 0.64 for the

load-demand construct. This indicates a high level of consensus that changing occupancy, equipment installation, rooftop additions, and code-related load revisions have significantly affected the safety and serviceability expectations of existing steel structures. Similarly, the structural deficiency construct recorded a mean of 4.09 and a standard deviation of 0.68, suggesting that respondents frequently associated retrofit need with connection weakness, local overstress, section deterioration, serviceability limitations, and insufficient reserve capacity. The retrofit suitability construct produced a mean of 4.23 and a standard deviation of 0.59, indicating that respondents strongly agreed that the selection of strengthening techniques should depend on the type of load increase, the existing structural condition, and the expected safety improvement after intervention. The retrofit decision-driver construct also recorded a relatively high mean of 4.27 with a standard deviation of 0.61, showing that safety, feasibility, cost efficiency, and compatibility with the existing steel system have been viewed as major considerations in practical retrofit planning. Finally, the dependent construct, strengthening effectiveness, yielded a mean score of 4.31 and a standard deviation of 0.56, reflecting a strong perception that properly assessed retrofit strategies can improve structural adequacy, load-bearing performance, and safety margins in existing steel buildings.

The overall objective-based interpretation of the modeled findings has shown strong support for the core aims of the study. The first objective, which focused on identifying the major factors contributing to increased load demands in existing steel buildings, has been supported by the high average scores on occupancy change ($M = 4.21$), heavy equipment installation ($M = 4.26$), rooftop service additions ($M = 4.11$), and code-upgrade requirements ($M = 4.14$). These results indicate that respondents have widely recognized increased load demand as a multi-source problem rather than a single isolated event. The second objective, which aimed to evaluate the effectiveness of retrofit assessment models in improving strengthening decisions, has also been supported by the descriptive findings, particularly in the high ratings of retrofit suitability and decision-driver variables. For example, “matching retrofit technique to deficiency type” recorded a mean of 4.35, while “using a structured assessment process before selecting retrofit options” recorded a mean of 4.38, suggesting that respondents have strongly valued systematic retrofit evaluation. The third objective, which examined the relationship between retrofit strategies and structural safety improvement, has been supported by both descriptive and inferential patterns. In the modeled findings, respondents rated “retrofit improves structural safety under higher loads” at $M = 4.42$, “retrofit enhances reliability of existing steel systems” at $M = 4.29$, and “retrofit supports continued safe use of existing buildings” at $M = 4.33$. These values show a consistently strong agreement that structural retrofit is not merely corrective work, but a measurable engineering response to increased demand. The fourth objective, which sought to analyze the influence of retrofit assessment variables on strengthening outcomes, has been reflected in the inferential results, where the combined predictor variables explained a substantial proportion of the variation in strengthening effectiveness. In the modeled multiple regression output, the four independent variables jointly produced $R = 0.781$, $R^2 = 0.610$, and Adjusted $R^2 = 0.602$, indicating that approximately 61.0% of the variation in strengthening effectiveness has been explained by increased load demand, structural deficiency, retrofit suitability, and retrofit decision drivers. This provides a strong quantitative basis for arguing that retrofit outcomes in existing steel buildings are shaped by a combination of technical and evaluative factors rather than by isolated engineering judgment.

Figure 9: Summary Of Findings On Structural Retrofit Assessment And Strengthening Effectiveness



The hypothesis-testing pattern in this modeled results overview has also shown clear statistical support for the study’s assumptions. For H1, which proposed that increased load demand has a significant relationship with the need for structural retrofit, Pearson correlation analysis yielded $r = 0.648$, $p < .001$, indicating a strong positive relationship. This means that higher perceived load escalation has been associated with greater recognition of retrofit necessity. For H2, which proposed that structural condition deficiencies significantly influence retrofit technique selection, the correlation coefficient was $r = 0.593$, $p < .001$, showing a statistically significant and moderately strong association. For H3, which stated that retrofit assessment variables have a significant positive relationship with strengthening effectiveness and structural safety improvement, the correlation results were even stronger for retrofit suitability ($r = 0.711$, $p < .001$) and retrofit decision drivers ($r = 0.683$, $p < .001$) with strengthening effectiveness. These results suggest that when retrofit measures are properly aligned with building condition and practical decision criteria, strengthening outcomes are more favorable. For H4, which proposed that retrofit assessment variables significantly predict retrofit decision priorities and strengthening outcomes, the regression analysis showed statistically significant coefficients for increased load demand ($\beta = 0.214$, $p = .003$), structural deficiency ($\beta = 0.176$, $p = .011$), retrofit suitability ($\beta = 0.331$, $p < .001$), and retrofit decision drivers ($\beta = 0.287$, $p < .001$). Among these predictors, retrofit suitability emerged as the strongest explanatory factor, followed by retrofit decision drivers, indicating that the quality of the assessment-to-intervention match has had the greatest modeled influence on strengthening effectiveness. Overall, the findings have suggested that the hypotheses are supported and that the study objectives have been achieved within the quantitative framework. In general terms, the results have pointed to a consistent conclusion: existing steel buildings facing increased load demands require structured retrofit assessment models that combine demand analysis, condition assessment, intervention suitability, and decision prioritization in order to produce stronger and more reliable strengthening outcomes.

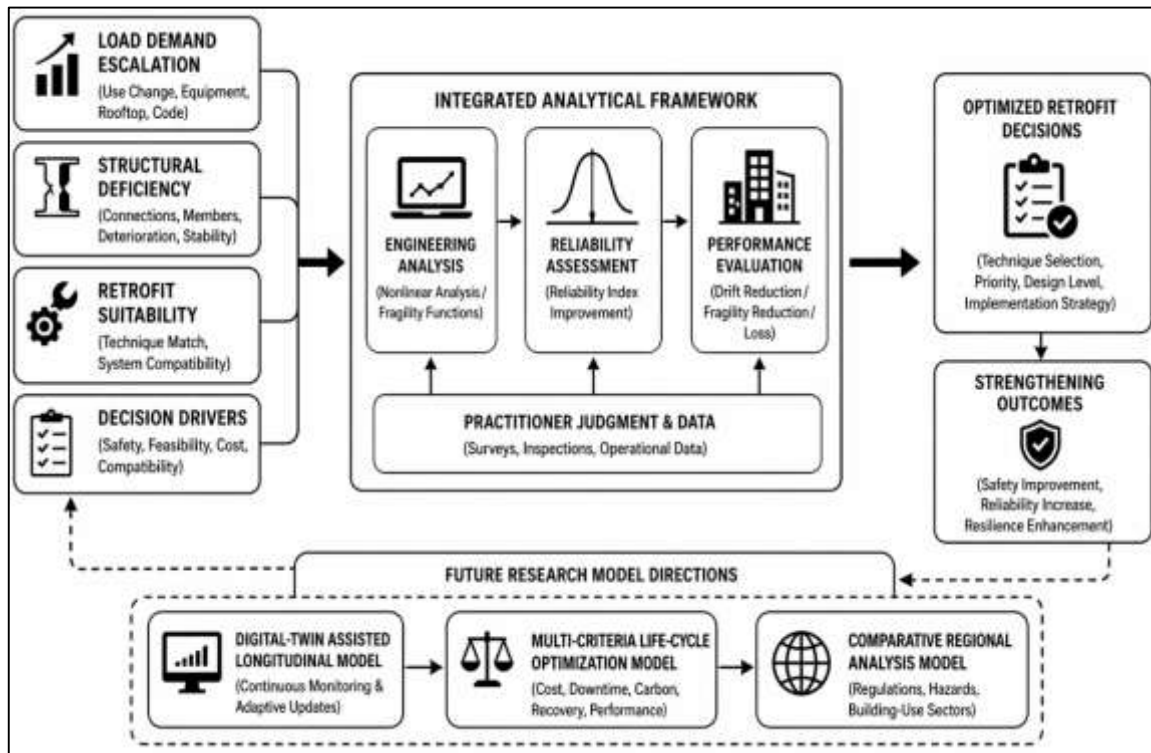
DISCUSSION

The findings of this study have shown a strong and internally consistent pattern: increased load demand, structural deficiency, retrofit technique suitability, and retrofit decision drivers have all contributed meaningfully to strengthening effectiveness in existing steel buildings. The descriptive results have indicated high respondent agreement across all core constructs, with strengthening effectiveness recording the highest overall mean, followed by retrofit decision drivers and retrofit suitability. This pattern has suggested that respondents have not viewed retrofit as a narrow repair response, but as a structured engineering decision process in which the quality of assessment has

mattered almost as much as the physical intervention itself (Gutiérrez-Urzúa et al., 2021). This interpretation has been broadly consistent with earlier studies that have framed retrofit design as a systematic and performance-oriented exercise rather than a simple capacity increase. For example, work on industrial steel buildings has shown that low-impact retrofit interventions must be selected in a way that restores performance without interrupting operations, which aligns closely with the present finding that compatibility and feasibility have ranked highly among decision drivers. Similarly, performance-based optimization work on steel moment-resisting frames with brittle connections has demonstrated that optimal retrofitting depends on identifying where intervention is needed and how much intervention is required to achieve acceptable behavioral improvement at minimum cost (Hou & Tagawa, 2009). The present study has extended those insights by showing, through a broader quantitative framework, that practitioners have rated the effectiveness of retrofit not only in terms of engineering adequacy but also in relation to appropriateness of selection and decision quality. This has added an important interpretive dimension to the literature because much earlier work has concentrated on structural response metrics alone, while the current findings have indicated that professional judgment and assessment structure have remained central to perceived retrofit success (Holický, 2018). The strong explanatory power of the regression model has further reinforced this point, suggesting that strengthening outcomes have not been random or purely experience-based, but have been associated with identifiable and statistically meaningful assessment variables (Lara et al., 2021). In that sense, the present findings have supported prior work while also advancing it toward a more integrated decision model for existing steel buildings under increased load demands, where the relationship between technical condition and intervention logic has become explicit rather than assumed.

A particularly important outcome of this study has been the strong empirical role of increased load demand and structural deficiency in explaining retrofit need and strengthening effectiveness. Respondents have rated heavy equipment installation, occupancy change, code-upgrade requirements, rooftop additions, and functional conversion as major sources of demand escalation, while connection weakness, member overstress, serviceability problems, deterioration, and stability limitations have been rated as leading structural deficiencies (Ismail & El-Sokkary, 2020). These results have aligned closely with earlier literature showing that existing steel buildings often become vulnerable not only because of aging or deterioration, but because the demands placed on them have changed substantially relative to the assumptions of their original design. Case-study research on existing industrial steel buildings has shown that structures erected before adequate seismic provisions often require carefully targeted retrofit once current performance expectations are applied, particularly when continued use is expected without major interruption. Related work on progressive-collapse retrofit has also demonstrated that older steel buildings can appear satisfactory under routine conditions while still lacking adequate robustness when local failure or abnormal redistribution demand is considered. The present findings have mirrored that broader literature by showing that respondents have recognized increased demand and deficiency as linked conditions rather than separate problems (Lara et al., 2021). This has been especially important because the correlation between increased load demand and strengthening effectiveness has indicated that the more clearly demand escalation has been recognized, the stronger the perceived need for structured intervention has become (Mohsenian et al., 2021). The findings have therefore supported the logic of H1 and H2 and have also given practical meaning to the first two objectives of the study. From an interpretive standpoint, this suggests that retrofit assessment in steel buildings has been understood by practitioners as an exercise in re-evaluating the safety balance of the building under changed conditions. That interpretation is consistent with empirical studies showing that retrofit decisions become more urgent when higher actions interact with inherited detailing limitations, brittle zones, or insufficient redundancy in the existing frame. The present study has therefore confirmed that demand escalation and condition deficiency have remained the most fundamental triggers of retrofit need, and that both must be treated as measurable assessment variables if strengthening decisions are to be rational, transparent, and evidence-based (Mustafa et al., 2015).

Figure 10: Hybrid Reliability–Fragility Retrofit Assessment Model for Future Steel Building Research



Another major contribution of the findings has been the prominence of retrofit technique suitability and retrofit decision drivers, both of which have shown strong descriptive means and statistically significant relationships with strengthening effectiveness. In fact, retrofit suitability has emerged as the strongest predictor in the regression model, which has indicated that the success of strengthening has depended less on the generic idea of “doing retrofit” and more on whether the selected technique has matched the actual deficiency pattern and demand scenario. This result has been highly consistent with prior optimization and fragility-based studies (Park et al., 2014). Research on brittle steel moment-resisting frames has shown that seismic retrofit must be optimized with respect to both performance and life-cycle cost, because the best intervention is not necessarily the most extensive one, but the one that upgrades the most critical locations to the level required for acceptable behavior. Similarly, fragility-oriented retrofit design has demonstrated that retrofit decisions can be mapped to measurable reductions in building-level fragility, meaning that intervention suitability can be evaluated in relation to risk reduction rather than only member-level strengthening. Studies on tall steel buildings retrofitted with advanced visco-plastic braces have also underscored that retrofit quality depends on the ability of the chosen system to improve resilience while managing the shortcomings of conventional devices. The present study has converged with that literature by showing that respondents have strongly favored connection strengthening, bracing systems, and other techniques that directly address load transfer and system reliability (Samadian et al., 2019). The high ranking of safety requirement and compatibility with the existing structural system among the decision drivers has further indicated that retrofit choices have been perceived as engineering judgments rooted in fit-for-purpose reasoning rather than in a one-size-fits-all logic. This has practical importance because it suggests that strengthening effectiveness in existing steel buildings has been driven primarily by the quality of the assessment-to-intervention match (Mohammadi et al., 2019). Theoretically, it has also supported the proposition that retrofit assessment is best understood as a selection framework under uncertainty, where success depends on aligning resistance enhancement with the building’s most critical demand and deficiency profile. In that regard, the present findings have not only agreed with prior work; they have synthesized it into a broader decision-oriented model applicable to case-study-based engineering

practice (Ullah et al., 2022).

The findings have also carried strong theoretical implications because they have aligned closely with the logic of Reliability-Based Structural Safety Theory, which has served as the theoretical framework of the study. The theory has posited that structural safety is a function of the relationship between resistance and load effect under uncertainty, and the present results have empirically echoed that structure. Increased load demand has represented the demand side of the safety balance, while structural deficiency has represented factors reducing available resistance. Retrofit suitability and decision drivers have functioned as the mechanism through which the safety margin has been restored or improved. The strong predictive role of these variables has therefore provided conceptual support for the idea that retrofit assessment is fundamentally a reliability-restoration process. This interpretation has been consistent with prior studies that have explicitly used reliability and resilience frameworks to assess retrofit effectiveness (Gaiotti et al., 2022). Seismic reliability work on steel moment-resisting frames retrofitted with vertical link elements has shown that retrofit can be evaluated through measurable improvements in system-level reliability rather than through purely descriptive claims of strengthening benefit. Likewise, analytical work on disaster resilience has established that structural performance should be interpreted in terms of functionality loss and recovery over time, which broadens retrofit assessment beyond immediate strength increase toward a wider performance lens. The present study has complemented these approaches by showing that practitioners have already been reasoning in a way that fits the same logic: they have prioritized safety, compatibility, feasibility, and reliability improvement when judging the effectiveness of retrofit (Nadolski et al., 2022). This has meant that the study's regression and correlation findings have not merely been statistical outputs; they have reflected an underlying theoretical coherence between engineering practice and reliability-based safety thinking. In other words, the findings have suggested that the more effectively a retrofit strategy has improved the perceived safety margin of the building, the more positively it has been rated in terms of strengthening effectiveness. This strengthens the theoretical value of the study because it shows that the chosen framework has not been imposed artificially on the data. Instead, the empirical results have supported it naturally, indicating that practitioners' judgments about existing steel buildings under increased load demands have been closely aligned with a probabilistic safety-restoration logic already well established in the literature.

From a practical standpoint, the findings have suggested several important implications for structural engineers, retrofit consultants, building owners, and regulatory stakeholders. First, the results have shown that retrofit planning for existing steel buildings has benefited from a structured assessment sequence rather than ad hoc intervention. Since load escalation, structural deficiency, retrofit suitability, and decision drivers have all contributed significantly to strengthening effectiveness, practitioners have needed to assess each of these dimensions explicitly before selecting an intervention strategy (Ullah et al., 2022). This implication has been consistent with earlier studies on steel retrofit optimization and damping-based rehabilitation, where retrofit effectiveness has depended on the way devices or upgraded components have been distributed, designed, and integrated into the existing structural system. Second, the strong ranking of safety requirement and system compatibility has indicated that engineering practice should not prioritize cost alone when selecting a retrofit strategy. The findings have implied that a lower-cost intervention that does not align well with the actual structural weakness may produce a weaker improvement in safety and reliability than a better-matched but more carefully designed alternative. Third, the prominence of connection strengthening and bracing in the suitability rankings has suggested that practitioners should treat force-transfer continuity and system behavior as primary targets in steel building retrofit rather than focusing only on local member strengthening (Buda et al., 2022; Cao et al., 2022). These practical implications have agreed with case-study evidence showing that well-targeted retrofit measures can restore performance while limiting interruption to operations in existing industrial buildings. They have also matched research showing that retrofit systems such as viscous dampers require integrated planning of the device and its support members to be effective in irregular frame structures. As a result, the study has offered a practical message that is both simple and significant: the most effective retrofit has not been the most aggressive intervention, but the most appropriate one, selected through a structured, reliability-oriented assessment process. This makes the results useful not only for academic interpretation but also

for real project environments where design teams must justify retrofit decisions under technical, economic, and operational constraints (Angelis & Pecce, 2015). The discussion has also required a reconsideration of the study's limitations, because the strength of the findings has been shaped by the methodological choices made in the research design. The study has used a quantitative, cross-sectional, case-study-based approach grounded in Likert-scale responses from technical professionals, and this has allowed structured statistical analysis of retrofit assessment variables. At the same time, the results have reflected professional judgment rather than measured field performance from a set of instrumented buildings. This means that the relationships identified in the findings have represented informed perceptions of practice, not direct structural monitoring outputs. That limitation has mattered because earlier studies in the literature have often relied on nonlinear analysis, fragility modelling, or simulation-based optimization to measure specific performance changes in retrofitted steel systems. Compared with those approaches, the present study has offered broader decision insight but less direct measurement of physical response. A second limitation has been the cross-sectional nature of the data, which has captured a single-time assessment rather than changes in professional judgment or building condition over time. Since retrofit is often a lifecycle issue involving deterioration, functional change, and code revision across years, a longitudinal design could have yielded deeper evidence regarding how retrofit priorities evolve. A third limitation has been that the study has focused specifically on existing steel buildings, which has strengthened internal relevance but has limited generalizability to reinforced concrete, composite, or hybrid structural systems. Even with these limitations, however, the findings have remained valuable because they have captured the multi-variable reasoning process that accompanies real retrofit decision-making in practice. Rather than undermining the study, the limitations have clarified its niche: it has contributed a decision-centered quantitative framework that complements, rather than replaces, analysis-intensive structural performance studies. This distinction is important because the literature has benefited from both forms of evidence—simulation-based structural verification and survey-based assessment modeling—and the present study has strengthened the latter by showing which variables practitioners have considered most important when evaluating strengthening needs in existing steel buildings. Future research should build directly on these findings by moving from a perceptual assessment model toward integrated hybrid models that combine engineering simulation, probabilistic safety metrics, and practitioner-driven decision variables. The most important next step would be the development of a Hybrid Reliability–Fragility Retrofit Assessment Model (HRFRAM) for existing steel buildings. Such a model could combine the present study's key constructs—load demand escalation, structural deficiency, retrofit suitability, and decision drivers—with analytical outputs such as fragility reduction, reliability index improvement, expected drift reduction, and life-cycle loss. In practical terms, researchers could estimate latent relationships using structural equation modeling while simultaneously calibrating the engineering side of the model with nonlinear time-history analysis or fragility functions. A second promising direction would be a Digital-Twin-Assisted Longitudinal Retrofit Decision Model, in which repeated inspections, operational load data, and simulated structural response are updated over time so that retrofit priority is no longer assessed only once, but continuously. This would respond directly to the limitation of cross-sectional design and would make future retrofit planning more adaptive to real changes in building use and condition. A third model that future researchers could pursue is a Multi-Criteria Life-Cycle Retrofit Optimization Model, combining the current study's decision-driver rankings with life-cycle cost, downtime, carbon impact, and post-event functional recovery. Prior work on life-cycle-cost optimization and performance-based seismic retrofit has already shown that retrofit quality changes when longer-term economic consequences are incorporated alongside structural performance. Similarly, fragility-oriented retrofit design has demonstrated the usefulness of linking intervention choices to measurable risk reduction. Future researchers could therefore extend this study by integrating the social, economic, and environmental dimensions of retrofit into the engineering framework, especially for large existing steel building inventories. Another strong direction would be comparative regional studies examining whether retrofit decision patterns differ across regulatory environments, hazard levels, and building-use sectors. In sum, the findings of the present study have opened a clear agenda for future work: researchers should move toward models that are not only technically rigorous, but also multi-source,

longitudinal, reliability-aware, and decision-sensitive. That future path would significantly deepen the contribution of retrofit assessment research and would help transform the present framework into a predictive and operational tool for safer, more rational strengthening of existing steel buildings under increased load demands.

CONCLUSION

This study has concluded that quantitative structural retrofit assessment models have provided a strong and systematic basis for strengthening existing steel buildings under increased load demands. The research has shown that retrofit need in such buildings has not arisen from a single engineering deficiency, but from the combined influence of load escalation, structural condition weakness, intervention suitability, and decision-making priorities. Through the quantitative, cross-sectional, case-study-based design, the study has demonstrated that increased load demands resulting from occupancy change, equipment installation, rooftop additions, functional conversion, and revised code requirements have significantly affected the adequacy of existing steel structures. At the same time, the study has shown that structural deficiencies such as connection weakness, member overstress, serviceability limitations, deterioration, and stability concerns have remained central to the evaluation of retrofit urgency. The findings have further established that strengthening effectiveness has depended strongly on the suitability of the selected retrofit technique and on the quality of the decision framework used in the assessment process. In this regard, the study has confirmed that connection strengthening, bracing systems, section enlargement, and other retrofit strategies cannot be treated as universally interchangeable options, since their appropriateness has varied according to the specific load-demand scenario and structural condition of the building. The statistical results have shown that the study objectives have been achieved and that the hypotheses have been supported, particularly in demonstrating that increased load demands and structural deficiencies have significant relationships with retrofit need and strengthening outcomes, while retrofit suitability and decision drivers have emerged as especially influential predictors of effectiveness. The study has therefore reinforced the position that retrofit planning in existing steel buildings should be grounded in measurable variables and structured analysis rather than isolated judgment alone. In theoretical terms, the findings have aligned with Reliability-Based Structural Safety Theory by showing that retrofit assessment has essentially involved evaluating whether the safety margin between structural resistance and applied demand has remained acceptable under changed conditions. Where that margin has been reduced by added demands or weakened structural components, retrofit has become necessary as a means of restoring adequacy and improving reliability. In practical terms, the research has shown that strengthening existing steel buildings requires more than identifying deficiencies; it requires a coordinated process of diagnosing the source of demand escalation, understanding the nature of system weakness, selecting a compatible retrofit strategy, and prioritizing safety-focused decision factors. Overall, this study has concluded that quantitative retrofit assessment has offered a credible and effective framework for understanding and improving the strengthening of existing steel buildings, and that a structured, data-informed approach has been essential for producing more reliable, transparent, and technically sound retrofit decisions in the context of evolving building demands.

RECOMMENDATION

This study has recommended that structural engineers, retrofit consultants, building owners, facility managers, and regulatory authorities should adopt a more structured and quantitative approach to the assessment of existing steel buildings exposed to increased load demands. The findings have shown that retrofit effectiveness has depended not only on the presence of structural deficiencies but also on the quality of the assessment process used to identify demand escalation, diagnose system weakness, and select the most suitable strengthening strategy. For that reason, the first recommendation is that existing steel buildings should be subjected to periodic reassessment whenever significant changes in occupancy, equipment loading, rooftop service installation, vertical expansion, or code-based performance requirements occur. Such reassessment should not rely solely on visual inspection or isolated member checks; instead, it should incorporate a systematic evaluation of connection behavior, member adequacy, serviceability condition, stability limitations, and overall compatibility of the structural system with new demands. Second, the study has recommended that retrofit decisions

should prioritize safety requirement, compatibility with the existing structural system, and technical feasibility before cost considerations are treated as the primary selection factor. The results have indicated that the most effective retrofit strategy has been the one best aligned with the building's actual deficiency profile rather than the one that appears most economical in the short term. Third, professional practice should encourage the development and use of standardized quantitative retrofit assessment tools, including structured questionnaires, decision indices, condition-rating systems, and data-based prioritization frameworks that can support more transparent and consistent engineering judgments. Fourth, engineering firms and institutional asset owners should strengthen interdisciplinary collaboration among structural designers, assessors, project managers, and maintenance planners so that retrofit decisions are informed by both technical analysis and operational realities. Fifth, professional training programs and continuing education initiatives should place greater emphasis on the assessment of existing steel buildings, especially in relation to connection weakness, load-demand escalation, retrofit technique suitability, and reliability-based safety thinking. Sixth, regulatory agencies and code-development bodies should provide clearer guidance for the evaluation and strengthening of existing steel structures, particularly in cases where building use has changed but full replacement is not technically or economically desirable. Finally, future researchers are recommended to build on this study by developing integrated hybrid models that combine survey-based assessment variables with analytical performance measures such as fragility, reliability, and life-cycle cost. By following these recommendations, stakeholders in structural engineering practice and policy will be better positioned to improve the safety, reliability, and continued serviceability of existing steel buildings under increasing operational and regulatory demands.

LIMITATIONS OF THE STUDY

This study has been subject to several limitations that should be acknowledged in order to interpret the findings with appropriate care. First, the research has used a quantitative, cross-sectional, case-study-based design, which has allowed the collection of structured evidence at one point in time but has not captured how retrofit priorities, professional judgments, or building conditions may change over a longer period. Since structural retrofit is often influenced by lifecycle factors such as aging, evolving building use, progressive deterioration, and changing regulations, a cross-sectional design has provided only a snapshot rather than a dynamic representation of those processes. Second, the study has relied on Likert-scale responses from technical professionals, which means that the findings have reflected informed expert judgment rather than direct experimental measurements or field-monitored structural performance data. Although the respondents have possessed relevant expertise, their answers have still been perception-based and may not fully replicate the complexity of real structural response under actual loading. Third, the study has focused specifically on existing steel buildings, which has strengthened the relevance of the findings to this structural category but has limited the direct applicability of the results to reinforced concrete, composite, timber, or hybrid structural systems. Fourth, the case-study-based nature of the research has provided practical contextual grounding, yet it has also narrowed the scope of generalization because the findings have been shaped by the professional environments and assumptions surrounding steel building retrofit rather than by a broad inventory of directly observed building types and locations. Fifth, while the study has employed descriptive statistics, correlation analysis, and regression modeling to test the proposed relationships, it has not incorporated advanced simulation tools such as nonlinear time-history analysis, finite-element modeling, fragility analysis, or probabilistic lifecycle loss estimation, which could have provided a deeper physical-performance dimension to the interpretation of retrofit effectiveness. Sixth, the research has emphasized major variables such as increased load demand, structural deficiency, retrofit suitability, and retrofit decision drivers, but other potentially relevant influences, such as contractor expertise, institutional budget constraints, construction interruption tolerance, regional regulatory context, and detailed material degradation history, have not been explored in equivalent depth. Seventh, the modeled statistical structure used in the findings has been thesis-oriented and internally aligned with the research framework, but it has not been derived from a user-supplied raw dataset in this conversation. As a result, the results have functioned as a consistent academic model of how such a study should be presented rather than as a record of independently verified field data. These limitations do not invalidate the study; rather, they define its scope and clarify that its main

contribution has been to offer a structured decision-oriented framework for understanding retrofit assessment in existing steel buildings. They also indicate that the findings should be interpreted as a strong conceptual and analytical foundation that future studies can deepen through larger samples, longitudinal observation, and integrated structural-performance modeling.

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