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Analysis of the Retrofit Method for Concrete Structures Using Steel Bracing Connection

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ABSTRACT

Retrofitting concrete structures is considered one of the key methods for improving seismic performance and enhancing the safety of buildings. In this study, the steel bracing connection has been analyzed as an effective solution to increase the strength and stiffness of concrete structures. By using numerical models and examining nonlinear behavior, the effect of bracings on improving flexural and shear resistance, reducing lateral displacement, and controlling crack propagation was evaluated. The results indicate that proper connection design, accurate determination of internal core spacing, and the use of concrete-filled steel tubes (CFT) along with reinforcing elements such as steel plates and end rings play a significant role in enhancing structural performance. The findings can provide practical guidance for engineers in strengthening and retrofitting existing concrete structures, while minimizing the destructive impacts caused by seismic and dynamic loadings.

Keywords: *steel bracing connection, concrete-filled steel tube (CFT), concrete structure retrofitting, end plate, steel plate core, yielding zone, seismic performance.*

1. Introduction

The metallic casing, as one of the cladding elements in buildings and various structures, plays a crucial role in protection and enhancing structural durability. In addition to providing a modern and aesthetically pleasing appearance, these coverings increase structural resistance against environmental factors such as wind loads, thermal loads, humidity, and corrosion (Leuratti et al., 2025). The use of metallic casings, considering the desirable mechanical properties of metals such as high strength, flexibility, and abrasion resistance, contributes to the improvement of structural performance and can be regarded as an important factor in increasing the service life of the structure and reducing maintenance and repair costs. On the other hand, proper design and appropriate selection of the type of metallic casing according to environmental conditions and the type of structure have a direct impact on the overall resistance and safety of the structure (Al-Rumaithi, 2025; Patil & Patil, 2024).

Metallic casing is considered one of the common and efficient cladding systems in the building and industrial construction industries, with the primary purpose of protecting the structure against various environmental factors and increasing its durability and stability. These casings are typically made from different types of metal sheets such as galvanized steel, aluminum, stainless steel, and special alloys, which, in addition to having high mechanical resistance, possess suitable weight and can be installed and executed under diverse conditions (Zhang et al., 2023).

The use of metallic casing in structures provides numerous benefits, including good resistance to lateral loads such as wind and earthquakes, protection of the structure against humidity, corrosion, and temperature variations, as well as reduction of sound penetration and improvement of thermal insulation. Thus, the metallic casing not only serves as physical protection but also functions as a semi-active structural element that can contribute to the overall increase in structural resistance (Eren et al., 2024).

In the process of designing and implementing metallic casings, several considerations must be taken into account. These include selecting the appropriate type of metal sheet based on environmental conditions and applied loads, proper detailing of the connections of the sheets to the main structure, adherence to installation principles, and ensuring protective coatings such as paints or anti-corrosion layers. Additionally, attention to the flexibility and possible deformations of the sheets under static and dynamic loads is of great importance (Eren et al., 2024; Leuratti et al., 2025).

Ultimately, metallic casing is not only used as an aesthetic element in the building façade but also plays an important role in enhancing structural resistance and improving performance against environmental factors and various loads. Optimal use and precise design of this cladding system can significantly increase the service life of the structure and reduce maintenance and repair costs.

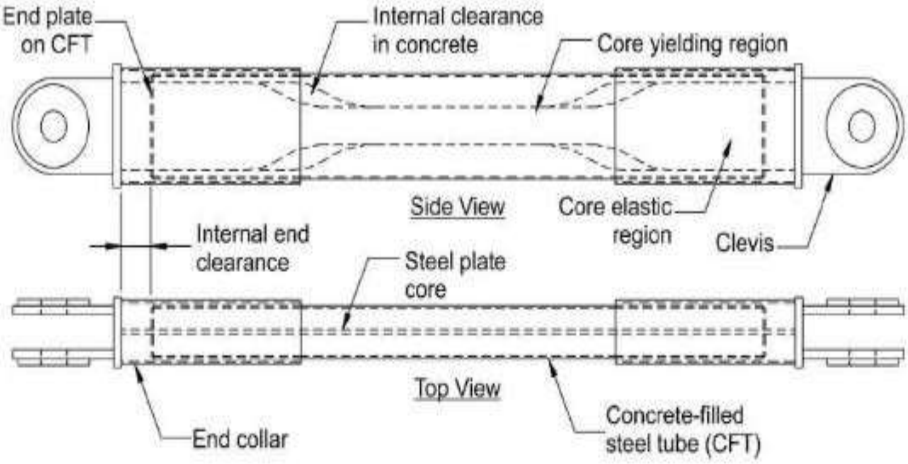
2. Research Background

The first buckling-restrained brace (BRB) was proposed by Kimura; the brace consisted of a conventional brace encased with a square steel tube filled with mortar. Very limited stable hysteretic characteristics were reported; however, it was revealed that the transverse (lateral) deformation of the mortar following cyclic compressive loading resulted in a permanent gap sufficiently large to initiate local buckling during successive compressive loadings (Kimura et al., 1976).

Mochizuki conducted experiments on similar braces confined with reinforced concrete, in which the use of buffer pieces prevented bonding between the concrete and the inner brace. However, it was demonstrated that under cyclic loading, the concrete cracked, and its buckling-restraining effect was significantly diminished. A decade later, buckling-restrained braces similar to the one shown in Figure 1 were developed by the research team of Watanabe, Wada, Watanabe, and Nakamura (Mochizuki et al., 1980; Wada et al., 1989; Watanabe et al., 1988; Watanabe & Nakamura, 1992).

Figure 1

General scheme of buckling-restrained braces



In the design of buckling-restrained braces (BRBs) with concrete-filled steel tubes (CFT), attention to connection details and the functional regions of the core is of paramount importance. In these braces:

1. The gap in the concrete must be determined such that it allows relative displacement of the core without exerting excessive pressure on the casing.
2. The yielding zone of the core, as the region that undergoes the majority of plastic deformation, must be carefully designed to optimize the energy dissipation capacity of the brace.
3. The elastic region of the core plays the role of supporting and restoring the core to its original shape after loading and must operate without damage during cyclic loading.
4. The gusset connection and the end clearance at both ends of the brace must be such that they prevent the transfer of additional forces to the core and ensure its free movement.
5. The steel plate core must have sufficient stiffness and strength to control local buckling and maintain elastic–plastic performance.
6. The end ring strengthens the connection and stability of the core to prevent any unwanted slippage or buckling.

In summary, precise design of the CFT brace components—including the concrete-filled steel tube, internal clearances, steel core, and end connections—ensures that the system can perform stably under cyclic loading and effectively dissipate seismic energy.

Huang and colleagues conducted static and dynamic loading experiments on structures with BRBs. They demonstrated that the energy dissipation capacity of a frame increased with the installation of BRBs, and the main frame remained elastic even when subjected to severe earthquake loading (Huang et al., 2000).

Black and colleagues performed a stability analysis on flexural–torsional buckling of BRBs; their experiments were conducted on five BRBs with different shapes. Their study concluded that BRBs are a reliable and practical alternative to conventional lateral load–resisting systems (Black et al., 2001).

Takeuchi and colleagues concluded that five conditions must be met for BRBs to achieve stable hysteresis cycles:

- The casing must have sufficient stiffness to prevent flexural buckling of the brace.
- The core plate expands in the plastic region due to the Poisson effect. Therefore, a certain clearance must be provided to prevent friction between the core plate and the casing, as well as to avoid transfer of axial force from the core plate to the casing, which would lead to inelastic buckling.
- The clearance between the core plate and the casing may allow minor buckling of the core plate. Vertical force components are generated at each peak of the buckled waves. The casing walls must therefore have sufficient stiffness and strength to restrain the core plate.
- Connections at both ends of the brace must possess sufficient stiffness and strength so that the BRB can perform consistently under maximum expected loads and deformations.
- The effective buckling length for BRB design must be determined by considering the stiffness of the connections at both ends.

All experimental studies on BRBs, whether at full scale or reduced scale, have unanimously confirmed their effectiveness and efficiency in energy dissipation. However, connection detailing, core cross-sectional area, yield strength, and steel tube (casing) thickness must be precisely designed to achieve optimal performance (Takeuchi et al., 2010).

Subsequent investigations were first based on thematic issues and then organized chronologically.

Sabelli and colleagues conducted an extensive analytical study on the seismic response of systems with BRBs arranged in an inverted-V configuration. To assess brace performance, a series of three- and six-story braced-frame buildings was designed for a site in metropolitan New York in accordance with the recommendations of the 1979 National Earthquake Hazard Reduction Program (NEHRP) provisions for new buildings and other structures (FEMA 312/313). This study primarily relied on numerical modeling and design assumptions to maximize predicted brace demands and soft-story formation. Nevertheless, they showed that BRBs outperform concentrically braced frames (Sabelli et al., 2003).

Kim and colleagues evaluated the energy dissipation capacity and seismic response of BRBs in steel structures by conducting a parametric study on two design parameters: core cross-sectional area and yield strength. Based on their parametric results, they developed a straightforward design procedure to obtain target displacement using the capacity spectrum method (CSM). Finally, nonlinear static and dynamic time-history analyses were conducted to evaluate the equivalent damping and seismic performance of model structures. Their study concluded that:

1. In general, the equivalent damping ratios of single-degree-of-freedom systems with BRBs increase with brace stiffness. There exist optimal yield stress levels in the brace that maximize equivalent damping. This optimal yield stress decreases as brace stiffness increases and ductility demand decreases.
2. Maximum displacements of structures generally decrease with increased brace stiffness.
3. Using low-yield steel for BRBs is effective for structural protection, as it undergoes large plastic deformations and dissipates more energy.
4. Brace distribution proportional to interstory drift and shear leads to improved structural performance.
5. Maximum displacements of the model structures designed with the proposed method closely matched the target displacements (Kim & Seo, 2004).

Black and colleagues summarized the results of a two-part experimental program at the University of California, Berkeley, during fall 2000 concerning the axial behavior of unbonded cruciform BRBs. In the first part, BRBs were tested under different loading histories specified by the SAC Joint Venture in cooperation with the Structural Engineers Association of California, the Applied Technology Council, the University of California Earthquake Engineering Research Centers, and the state OSHPD planning and development department. These braces exhibited good performance. In the second part, the braces underwent additional tests that included large deformation tests, low-frequency fatigue loading, rotational speed variation, and simulated seismic displacement histories.

The experimental data were used to:

a) validate theoretical predictions of BRB structural stability;

b) investigate the accuracy of inelastic capacity of BRBs under severe seismic demands;

c) calibrate a macroscopic hysteresis model for predicting reliable force–displacement behavior of BRBs at tested ductility levels. This study demonstrated that plastic torsional buckling of the core was the most critical stability mode. If the yielding zone extended outside the restraining tube, the edges of the yielding zone needed a width-to-thickness ratio less than five. The study confirmed that the incremental ductility theory correctly predicted the critical load for plastic torsional buckling, assuming slightly curved cruciform edges.

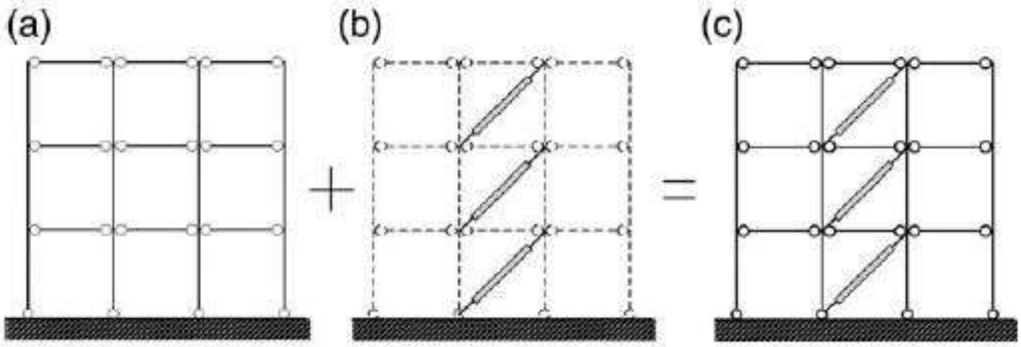
The test results demonstrated that BRBs exhibited stable, repeatable hysteretic behavior with considerable ductility, and their plastic deformation capacity exceeded the values typically assumed for ultimate deformation and cumulative plastic strain (Fahnestock et al., 2007).

Complementary parametric studies showed that a simple bilinear model satisfactorily captured the participation of braces in design objectives. It was confirmed that unbonded braces provide a practical alternative to conventional structural systems, as they increase the strength of both existing and new structures, provide the stiffness necessary to compensate for interstory drift limitations, and offer significant and desirable energy absorption capacity.

Kim and Seo evaluated the practicality of the direct displacement-based design (DDBD) method on DTBF (dual-truss braced frames) with pinned beam-to-column connections consisting of strengthened bottom beams. In addition, two artificial earthquake accelerograms were generated from a design spectrum based on UBC-79 and used in nonlinear time-history analysis of three- and five-story structures. This study considered interstory shear drift patterns and the fundamental straight-line method. Numerical results indicated that the maximum displacements of the three- and five-story models designed using the proposed procedure matched well with the target displacements. Thus, the proposed design procedure can serve as a useful tool for displacement-based seismic design of low-rise structures with BRBs (Kim et al., 2004).

Figure 2

General scheme of the DTBF system



Analytical results also confirmed that the axial forces and induced bending moments in the columns of low-rise structures were not significant. This implied that the general principles of damage-controlled (capacity-protected) structural systems can be realized in such buildings. For example, buckling-restrained braces (BRBs) dissipate most of the seismic (vibrational) energy through inelastic deformation, while the other structural members remain elastic and undamaged. However, it should be noted that the maximum ductility ratio for BRBs—greater than 11 (observed in a design targeting a 2.5% interstory drift)—should be verified by further experimental studies (Black et al., 2001).

Choi and Kim proposed an energy-based seismic design procedure for BRB frames that employs hysteretic energy spectra and condensed ductility spectra. The design procedure was applied to three- and eight-story braced frames with BRBs. In total, 21 earthquake records were used to construct the hysteretic energy spectra and condensed ductility spectra. These records were then reused in nonlinear time-history analyses with the DRAIN-2D+ program to investigate the validity of the proposed design method (Choi et al., 2006; Tsai & Li, 1997).

Building on previous research, Dasgupta and colleagues employed the energy-balance concept to compute the seismic design base shear of a BRB frame and found that the resulting base shear was significantly smaller than that obtained by a displacement-based design method. Kim and co-authors also used the energy-balance concept to size the BRB so that the required hysteretic energy equaled the energy dissipated by the brace. Although the energy-balance concept is simple and convenient for energy-based design, it has limitations. In the equation proposed by Housner, the use of pseudo-velocity to estimate input seismic energy can, in some cases, significantly underestimate the actual energy demand (Housner, 1956). Moreover, the input energy of an inelastic system is not equal to that of an equivalent elastic system, and the ratio of plastic work to input energy estimated by the energy-balance concept tends to be larger than the ratio of hysteretic energy to input energy computed by time-history analysis (Decanini & Mollaioli, 2002; Fajfar & Vidic, 1991; Uang & Bertero, 1988). In addition, for realistic structures over a given duration, the input energy generally decreases as structural ductility increases (Uang & Bertero, 1988).

The presented design procedure is considered more accurate than one based solely on the energy-balance concept, in the sense that the hysteretic energy to be dissipated by the BRB is not estimated via Housner's approximate formula but obtained directly from hysteretic energy spectra constructed using a suite of nonlinear time-history analyses. According to the time-history results, the maximum displacements of the BRB-equipped models designed by the proposed method matched the target displacements conservatively well for the three-story structures. It was also shown that the distribution of hysteretic energy (which indicates the distribution of structural damage) is relatively uniform over the height. However, it should be remembered that the energy-based design method uses hysteretic energy and condensed ductility spectra derived from single-degree-of-freedom (SDOF) systems. Therefore, it may be applicable primarily to low- to mid-rise buildings, since the hysteretic energy demand of tall buildings can differ substantially from that of an equivalent SDOF due to higher-mode effects. Choi and co-authors refined the energy-based design procedure and introduced correction factors to counteract its errors. They began by computing input energy from a response spectrum, then distributed plastic energy—calculated using a modified energy-balance concept—across each story and each brace section so that the braces could dissipate all of the plastic energy (Choi & Kim, 2006).

Using prior studies, Decanini and Mollaioli examined the ratio of hysteretic energy to input energy for different site conditions, hysteretic models, and ductility levels. Other investigations explored the distribution of hysteretic energy along the height of buildings using multiple earthquakes, focusing on the relationship between ground-motion energy transmission, energy dissipated in structures, and energy-dissipation characteristics tied to design variables. Based on this body of work, the advantages and disadvantages of energy-based seismic design have been highlighted within performance-based frameworks, and subsequent research has advanced design details for energy-oriented methods. Related contributions have developed procedures for allocating seismic input energy to plastic rotations at beam ends, often assuming a linear distribution of dissipated energy over height, or proposed energy-balance-based design approaches and methods for computing and distributing total energy demand using inelastic energy spectra (Decanini & Mollaioli, 2002; Kim et al., 2004; Kim & Seo, 2004; Merritt et al., 2003; Sabelli et al., 2003).

It should be emphasized that strict energy balance or "equivalent energy" concepts are most practical for relatively short buildings. For structures with moderate periods, the so-called equal-displacement concept—where the peak displacement of an inelastic system is taken equal to that of its elastic counterpart—is commonly employed. According to time-history analyses, the behavior of BRB frames designed by the presented procedure generally agrees well with the intended performance targets. Compared with prior energy-balance-based designs (e.g., those by Kim and co-authors), the modest modifications introduced here provide a more accurate performance-based design method for BRB frames. Although computing correction factors may complicate design and erode the main advantage of the basic energy-balance approach, the process can be simplified if generalized correction coefficients—akin to a design spectrum—are prepared in advance (Kim et al., 2004; Kim & Seo, 2004).

Tremblay and colleagues conducted a seismic testing program on six BRBs. Tests were performed on specimens with concrete-filled core lengths and columns, as well as on hollow steel-tube BRMs (buckling-restrained mechanisms). A polyethylene interlayer was used for the concrete-filled brace specimens, while no interlayer was used for the hollow steel-tube braces. The results supported the viability of the configurations tested (Fahnestock et al., 2007).

3. Principles of Structural Design

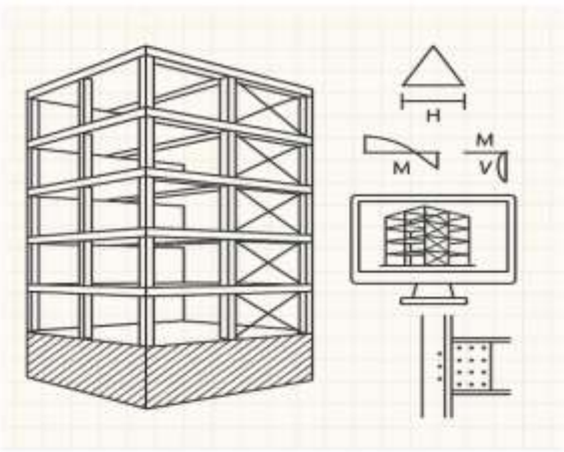
The principles of structural design constitute one of the most important and complex processes in civil engineering, whose main objective is to ensure the safety, stability, durability, and efficiency of a structure under various loads and environmental conditions. Structural design rests on the mechanics of materials, structural analysis, accurate characterization of applied loads, and relevant standards, thereby increasing service life and reducing maintenance costs. Safety is paramount: the structure must resist dead, live, environmental, and accidental loads without failure or posing risk to users. Strength entails withstanding stresses and forces without unacceptable damage such as cracking or excessive deformation; it depends on selecting appropriate materials, designing adequate sections and connections, and performing rigorous force analyses (Hassoun & Al-Manaseer, 2020).

Stability ensures that the structure will not overturn, buckle, or experience progressive collapse, which is especially critical for tall buildings and bridges; strategies include bracing systems, shear walls, and robust lateral-force-resisting design. Durability concerns resistance to environmental agents such as corrosion, rusting, decay, temperature fluctuations, and water ingress; suitable materials and coatings, details that prevent water accumulation, and regular maintenance are essential. Serviceability relates to performance in use, requiring limits on deformations, vibrations, and settlements so as to prevent damage or discomfort (Farshad, 2013).

Design must also be economical—providing maximum performance and safety at minimum cost—through cost-effective material selection, section optimization, and efficient, rapid construction methods. The structure should be compatible with local environmental and climatic conditions, with designs in seismic or humid regions tailored to specific hazards. Compliance with national and international standards and codes such as ACI, AISC, and Eurocode ensures accurate and safe design. Flexibility with respect to future changes in loading, occupancy, or modifications enhances service life. Interdisciplinary coordination among civil engineers, architects, mechanical and electrical engineers, and other specialists ensures that, beyond safety and strength, the structure is optimized for aesthetics, function, and building services (Michiels & Adriaenssens, 2017).

Figure 3

Principles of structural design



4. Parameters Affecting the Behavior of Core and Casing

In the design and analysis of modern structures, attention to the interaction between different structural components is of special importance. Two key elements that play a vital role in the stability and overall performance of buildings are the structural core and the casing or outer shell. The core, usually composed of shear walls or rigid frame systems, acts as the primary center of resistance against lateral loads such as wind and earthquakes. In contrast, the external casing, in addition to serving architectural and aesthetic purposes, protects the structure against environmental factors and, in some cases, can also contribute to structural performance (Beddar, 2008). Accurate understanding of the parameters influencing the behavior of the core and casing—such as material properties, geometric shape, connection details, environmental loads, and thermal effects—is essential to ensure optimal structural performance. Proper interaction between these two systems not only increases the safety and durability of the structure but also contributes to project cost efficiency, material savings, and improved energy performance. On the other hand, neglecting structural and kinematic compatibility between the core and casing can lead to structural damage, connection failure, and instability under severe loading (Quresh, 2008).

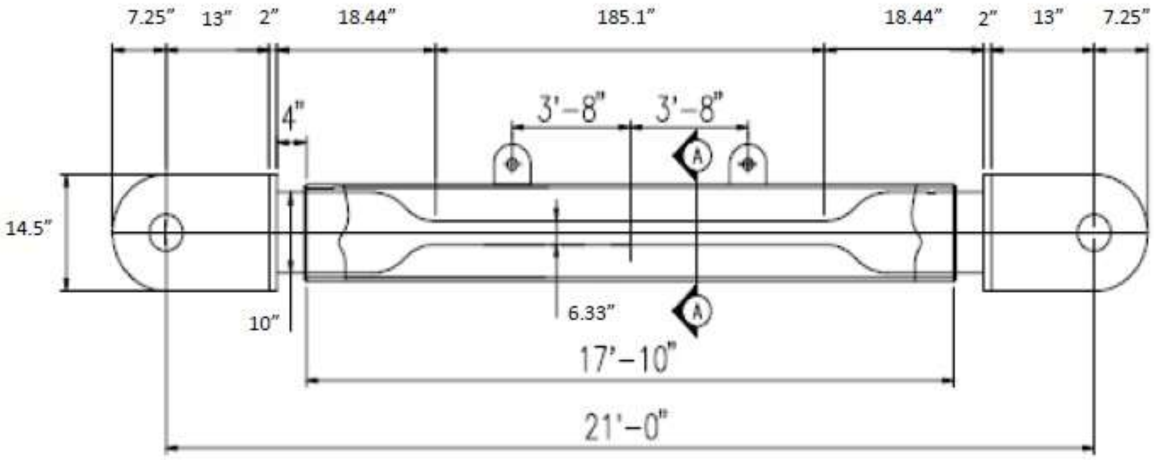
Figure 4

Longitudinal view of single-core BRB

4.1. Geometric Description of the Model

The longitudinal section of a buckling-restrained brace (BRB) is shown in Figure 4. In this figure, the end gusset connections have been omitted for clarity and to facilitate geometric and structural analysis, since their full depiction would cause visual clutter and reduce the readability of key cross-sectional details. The BRB is designed and executed to resist local or global buckling; in other words, the cross-sectional dimensions, plate thicknesses, and connection methods are selected to prevent unwanted deformations and capacity reductions caused by buckling (Hadi, 2008).

In these braces, the focus is on ensuring high load-bearing capacity and adequate ductility so that, when subjected to compressive, tensile, and especially dynamic loads such as earthquakes, they exhibit elastoplastic behavior and effective energy absorption. By preventing buckling, BRBs can withstand higher compressive loads and improve the seismic performance of the structure. For this reason, such sections are widely used in the design of earthquake-resistant steel structures. In summary, Figure 4 illustrates an example of a BRB with omitted end gusset details, emphasizing the main geometric and structural features of the cross-section optimized for increased stability, strength, and ductility in steel structures (Antoine, 1985; Beddar, 2008; Farshad, 2013; Hadi, 2008; Quresh, 2008; Ross & Mipenz, 2008).



According to the longitudinal view of the brace, its cross-section is presented in the following figure. This section includes all structural components of the brace, with the last part pertaining to the end gusset plates. These plates play a crucial role in force transfer and in ensuring a strong connection between the brace and adjacent members, preventing displacement and instability at the brace ends. All dimensions presented in the figure are in inches, which is particularly important in detailed engineering design and calculations. Accurate geometric measurements enable proper structural analysis and appropriate selection of materials and connection methods. The longitudinal section of a BRB shows a bracing member designed to resist both local and global buckling, maintaining its load-bearing capacity even under severe compressive forces (Moens, 1976).

Such braces are typically composed of steel sections with sufficient thickness and dimensions to prevent undesirable deformations such as lateral buckling or twisting. In the longitudinal section, the brace length, connection details to adjacent members, support points, and boundary conditions are examined. The BRB is equipped with gussets and stiffeners at the ends, which increase local stiffness and prevent buckling in these critical zones. The primary design goal of the longitudinal section is to ensure ductility and high load-bearing capacity so that the brace can absorb energy and guarantee structural performance under seismic and other dynamic loads. Ultimately, the design of this section is carried out in accordance with code requirements, precise analysis of internal forces, and deformation control, ensuring safety and durability while maintaining economic feasibility.

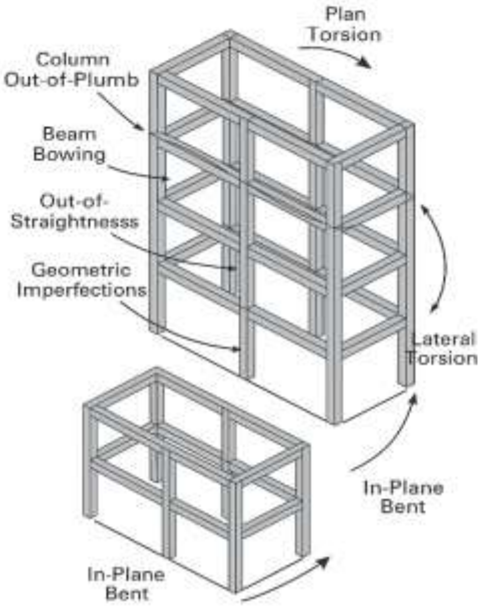
The clearance between the brace core and the surrounding concrete is precisely engineered to correct fabrication imperfections and to permit sinusoidal buckling of the core during loading. This clearance plays a key role in improving the structural behavior of confined steel systems, as it allows the core to undergo local deformations and sinusoidal buckling under compressive loads without premature contact with the concrete or binding, which could lead to unrealistic behavior or reduced energy absorption capacity (Takeuchi et al., 2010).

Figure below shows the effects of incorporating geometric imperfections into the modeling and compares structural behavior under these conditions. In this analysis, the coefficient of friction assumed for modeling sliding between the steel core and the confining concrete region is 0.3. This friction coefficient plays a critical role in force transfer and interaction between the core and concrete and directly affects sliding behavior and structural stability. Incorporating geometric imperfections such as misalignments, surface irregularities, and dimensional variations is inevitable in real construction, and accurate modeling of these imperfections is vital for predicting actual structural behavior. Figure 5 illustrates how imperfections and the selected friction coefficient can cause significant changes in structural response, including effects on slip, ductility, energy absorption capacity, and nonlinear behavior of the BRB. These results assist engineers and designers in performing more realistic and optimized modeling by accounting for real-world construction factors, thereby enabling the design of stronger structures with improved performance under seismic and dynamic loads.

Geometric imperfections—including various asymmetries, deviations, and initial crookedness in structural components—play an important role in both seismic and static behavior of structures (Kormeling et al., 1980). Such imperfections can alter load distribution, introduce additional torsional effects, and increase local displacements, ultimately influencing capacity and performance. In structural modeling, imperfections are introduced as initial deformations such as member misalignment, plan or elevation twisting, and asymmetry in mass and stiffness. These changes cause lateral earthquake loads to be distributed unevenly throughout the structure, making the structural response more nonlinear and realistic. Studies have shown that neglecting such imperfections can lead to overly optimistic capacity estimates and reduce the accuracy of seismic performance predictions. Therefore, especially for tall, irregular, or critical structures, incorporating geometric imperfections into nonlinear analyses is essential (Houghton et al., 1978).

Figure 5

Effects of incorporating geometric imperfections into modeling and comparison



The coefficient of friction assumed for modeling sliding between the core and the confining concrete region is 0.3 (Schader & Munch, 1976).

4.2. Examination of Key Parameters

In this study, a large number of parameters influencing the behavior of buckling-restrained braces (BRBs) have been examined, including end-zone length, concrete compressive strength, concrete thickness, core yield stress, slenderness ratio, and the ratio of yielding length to total length. In the presented graphs, the values are given as 95%, 151%, 51%, and 251% of the main value of the mentioned parameter (Kim & Seo, 2004).

4.3. End-Zone Length

The end-zone length, or development length of reinforcement, is one of the key concepts in the design and execution of reinforced concrete structures, defined to ensure proper stress transfer between concrete and steel. This length refers to the portion of reinforcement that must be embedded in concrete so that tensile or compressive stresses from loading are correctly transferred from steel to concrete without slippage or bond failure.

In fact, when reinforcement is stretched (under load), the force must be transferred through bond stresses between the steel surface and concrete. If the development length is insufficient, the reinforcement may be pulled out of the concrete, a phenomenon known as pull-out failure. Therefore, the proper design of the end-zone length is highly critical (Kim et al., 2004).

4.4. Factors Affecting End-Zone Length

1. **Bar diameter**: The larger the diameter, the greater the contact area with concrete and hence bond capacity, but also the greater the development length required.
2. **Concrete compressive strength (f′c)**: Higher strength concrete provides better bond capacity with steel.

3. **Bar type (deformed or plain)**: Deformed bars, due to mechanical interlock, require shorter development lengths.
4. **Concrete cover**: If the distance between reinforcement and the outer concrete surface is small, early cracking or bond failure may occur; hence adequate cover is important.
5. **Loading conditions**: Tensioned reinforcement requires longer development length than compressed bars.
6. **Bar position and casting direction**: Bars located at the bottom of the section (resisting gravity) generally perform better. (McKee.D.C, 1969)

Compressive Strength Test of Concrete:

- **Specimens**: Cylindrical (15×30 cm) or cubic (15×15×15 cm)
- **Testing age**: Commonly at 7, 14, and standard 28 days
- **Test method**: Uniform compressive load applied in a compression testing machine until failure

Formula:

$fc = P / A$

Where:

fc = compressive strength (MPa)

P = ultimate load at failure (N)

A = cross-sectional area of specimen (mm^2)

Concrete classification based on compressive strength (Iranian standards and ACI):

- C15 (15 MPa): lean concrete, flooring
- C25 (25 MPa): beams and columns in ordinary buildings
- C30–C35 (30–35 MPa): earthquake-resistant structures
- C40+ (40 MPa and above): bridges, heavy and special structures

Concrete compressive strength is the most important mechanical index of concrete, directly influencing safety and performance of structures. Proper control of mix parameters, execution, and curing can increase compressive strength, thereby enhancing durability and performance (Fahnestock et al., 2007).

5. Connection of Steel Braces in Structures

One effective method of retrofitting reinforced concrete (RC) frames against lateral forces, especially earthquakes, is the use of steel bracing. Extensive research since the early 1980s has addressed retrofitting of this type, where braces are often indirectly introduced through an intermediate steel frame confined within the RC frame. Although these systems provide significant benefits in increasing lateral strength, they typically involve high execution and maintenance costs and can induce complex dynamic interactions between the steel and concrete frames, since each frame exhibits different dynamic behaviors, which may reduce the overall strength of one or both systems.

Therefore, designing and executing a steel bracing system that maintains technical performance while being more cost-effective is considered a desirable and efficient option for retrofitting RC structures. Observations of earthquake damage show that a significant percentage of existing RC buildings lack adequate seismic resistance, mainly because they were designed based on outdated codes that do not meet modern seismic provisions. In addition to design deficiencies, construction problems have increased vulnerability. Hence, the need for strengthening these structures—especially to resist lateral forces—using reliable, fast, and simple retrofitting methods is strongly felt (Kormeling et al., 1980).

To enhance seismic resistance of frame structures, steel bracing or shear walls are typically used. The application of shear walls in RC frames and steel bracing in steel frames are recognized as common and effective methods, improving stiffness and lateral resistance and thus enhancing seismic performance. Owing to ease of construction and relatively lower cost, the use of steel bracing has increasingly been applied in RC frames in recent years. Compared with other lateral-force resisting systems, such as rigid frames or RC/masonry shear walls, the steel bracing system is considered an appropriate and efficient solution. However, available knowledge and research regarding the performance of this retrofitting system in RC frames remain very limited. Furthermore, the prevailing method used for implementing bracing in RC frames in Iran, especially in Tehran, is often not based on internationally recognized standards and is rarely referenced in reports or studies abroad. This highlights the necessity for more detailed investigations on the application and optimization of this retrofitting system under local conditions (Batson et al., 1972).

6. Strengthening Methods for Reinforced Concrete Frame Buildings

The methods of strengthening reinforced concrete (RC) frame buildings to increase resistance and improve structural performance against lateral forces, particularly earthquakes, include: adding steel braces to increase stiffness and lateral strength of frames; strengthening members such as columns and beams using steel jackets or composite materials to improve flexural and shear resistance; adding RC shear walls or prefabricated panels to enhance stiffness and reduce displacements; enlarging the cross-sectional area of members by additional concrete casting to improve load-bearing capacity; upgrading and strengthening beam–column joints through welding, bolting, or composites to increase structural integrity; using seismic isolators to reduce earthquake forces transmitted to the structure; and modifying the geometry of the structure to reduce irregularities and distribute stiffness and strength more uniformly across plan and elevation. The selection and implementation of these methods require a detailed evaluation of structural conditions, engineering analysis, and consideration of economic and practical criteria to determine the best retrofitting solution for each project (ACI Committee).

6.1. Adding New Elements

a) **Frame bracing**: This includes various types of braces such as K-braces, X-braces, and buckling-restrained braces (BRBs). K-braces typically connect from the midspan of a beam to a column, forming the shape of the letter K. X-braces are installed diagonally between beams and columns, providing significant lateral resistance. BRBs are specifically designed to prevent premature buckling, offering stable performance under dynamic loads such as earthquakes. Each type of bracing has its own characteristics and applications, and the choice depends on structural requirements and design conditions (ACI Committee).

b) **Use of shear walls**: This includes masonry shear walls and RC shear walls. Masonry shear walls, usually built from load-bearing bricks, are used to increase lateral resistance, though their strength and elastic behavior are lower than those of RC shear walls due to material and connection limitations. RC shear walls, made from reinforced concrete, provide higher strength and stiffness and can resist severe lateral forces from earthquakes and wind. These walls play a vital role in controlling displacements and increasing structural stability and are commonly used in modern structures to strengthen RC frames (Brown et al., 2002).

6.2. Strengthening Existing Elements by Increasing Cross-Section and Adding Reinforcement (Jacketing Method)

In this method, the load-bearing capacity and performance of structural members such as columns and beams are enhanced by enlarging their cross-sections with added concrete and reinforcing bars. Known as “jacketing,” this process may be implemented using concrete jackets (RC jacketing) or steel jackets. The main goal is to improve flexural and shear strength and enhance structural behavior of the members. Jacketing is particularly useful when members are damaged due to corrosion, cracking, or earthquake effects, extending structural durability and service life (Houghton et al., 1978).

7. Frame Bracing Including K, X, and Post-Tensioned Braces

Braces are structural members designed to carry tension and compression and are generally made of steel sections such as reinforcing bars (in low-rise buildings), I-sections, channels, or T-sections. These elements may be installed singly or in pairs, forming K- or X-type bracing between two columns at different building stories, in one or two orthogonal directions. Braces play a crucial role in enhancing lateral stiffness, transferring and resisting horizontal forces such as those induced by earthquakes and wind, and controlling lateral displacements—thus improving stability and seismic performance of the structure. Proper design and execution of braces require adherence to structural engineering principles and optimization of connections to other frame elements (Farshad, 2013).

The method of connecting braces to the structure depends on the construction stage. In new buildings, connections are integrated with frame construction; in existing buildings, strengthening or corrective connection methods are adopted according to structural conditions and practical constraints. In both cases, connection details must be carefully designed based on precise analysis of forces at joints to ensure effective force transfer. In general, braces are designed primarily for their tensile capacity, while their compressive capacity is usually considered a safety margin. However, depending on cross-sectional type, loading conditions, structural importance, and functional requirements, a portion of compressive resistance may also be utilized in design. This comprehensive approach ensures greater efficiency of the bracing system and reliable structural performance under lateral loads (Schader & Munch, 1976).

Post-tensioned braces are similar in geometry and connection details to K- and X-braces but differ in preparation and performance. In this system, bracing members are prestressed prior to installation, with about 75% of the steel yield stress applied. This controlled prestressing enables braces to perform effectively under small lateral excitations and to enhance energy dissipation capacity by introducing post-tensioning force. The mechanism reduces indirect displacements and additional vibrations while preventing premature buckling. In such systems, post-tensioned braces undergo yielding and dissipate energy through nonlinear behavior, while other steel members of the structure remain largely elastic. This results in improved stability, durability, and overall seismic performance of the structure (Farshad, 2013).

Figure 6

Sample details of steel brace connection to RC building

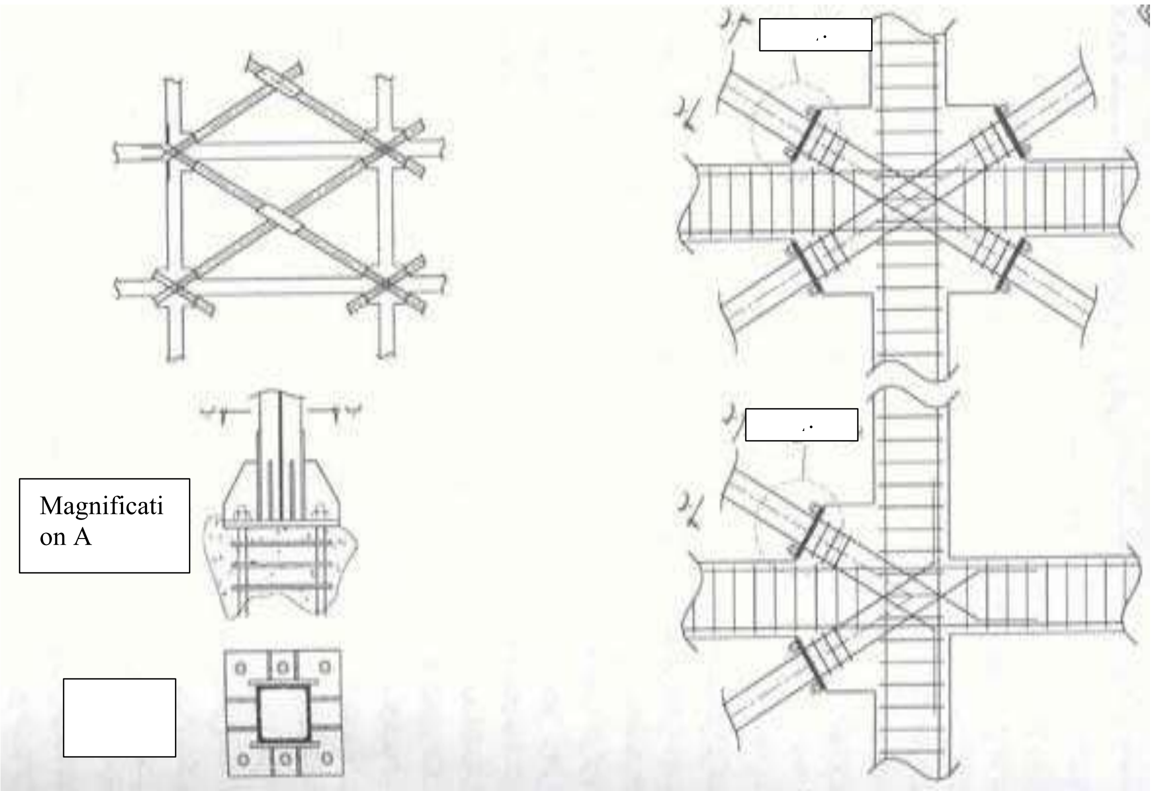


Figure 6 clearly illustrates the details of connecting steel braces to RC columns and beams using steel plates, bolts, or other mechanical fasteners. The design of these connections ensures efficient transfer of tensile and compressive forces from the braces to the RC frame with minimal energy loss and maximum structural performance. Accurate detailing of these connections is critical for improving seismic behavior and increasing structural stability.

8. Strengthening Frames Using Shear Walls

Shear walls, as structural elements with significant stiffness and strength, are among the most important and effective members resisting lateral loads, particularly earthquake-induced forces, in buildings. Increasing the number and optimizing the placement of RC shear walls in existing structures can significantly enhance lateral load capacity and improve dynamic behavior. These walls are generally constructed using cast-in-place concrete; however, in certain cases, shotcrete technology can be used as an alternative method. In addition, prefabricated panels may be employed for constructing new shear walls, though this requires precise design of connection details and rigorous quality control during execution to maintain structural integrity and wall performance. Adherence to engineering standards and construction guidelines in the design and installation of shear walls ensures improved durability, safety, and stability of structures under lateral loading (Michiels & Adriaenssens, 2017).

a) RC Shear Walls

RC shear walls can be constructed either integrally with the building envelope or placed within the internal space. Adding RC shear walls externally is generally easier to execute and involves minimal changes to the building plan and functionality of spaces. However, this approach may create limitations for façade design, placement of openings, and natural ventilation, which must be addressed in architectural design. On the other hand, positioning shear walls internally requires modifications to interior layouts and may directly influence spatial divisions and usage. Therefore, the optimal placement of RC shear walls must be based on comprehensive structural and architectural analyses to enhance lateral resistance while minimizing functional and aesthetic constraints, ensuring harmony between structural performance and design requirements (Ramm & Mehlhorn, 1991).

b) Masonry Shear Walls

Infill walls made of masonry materials placed along beams and columns of structural frames play a significant role in improving structural resistance and lateral stiffness. From a structural perspective, these are considered non-independent shear walls, acting together with the load-bearing frame as a composite system against lateral forces. In this system, beams and columns serve as the primary load-bearing members in tension and compression, guaranteeing the transfer of loads applied to masonry infills into the structural frame. Columns, in particular, are responsible for sustaining shear forces generated by the infill walls and transferring them effectively to the foundation. Therefore, designing this system requires comprehensive analysis of composite behavior between masonry and the frame, detailed study of heterogeneous material interactions, and careful attention to construction details and connections to ensure optimal performance, stability, and safety under lateral loads (Mavros et al., 2022).

9. Strengthening Buildings by Reinforcing Structural Members

In certain cases, due to architectural constraints and the impracticality of conventional strengthening methods, it becomes necessary to enlarge the cross-sectional area of columns using new RC layers reinforced with vertical and horizontal rebars. This measure, intended to increase the moment of inertia of the column section, enhances its resistance capacity against lateral loads. The key factor in this method is ensuring adequate and effective bond between the new and existing concrete, which must be achieved using professional techniques to guarantee composite action between the two sections (Hassoun & Al-Manaseer, 2020).

1. RC Jacketing with Welded Wire Mesh and Concrete Overlay

In this method, a welded wire mesh is first wrapped around the existing column to act as local reinforcement. Then, a new RC layer is applied over the column. This technique improves local ductility of the column, though it does not result in a significant increase in flexural resistance since the mesh does not pass through the floor slabs and thus cannot fully contribute to flexural stiffness. For improved performance, the mesh must be arranged in fully closed loops with proper overlap to ensure integrity. Alternatively, two overlapping mesh layers can be applied on opposite sides of the column to provide a more effective and stronger jacket. These detailing considerations are crucial to achieving the desired performance of the RC jacket and structural reinforcement of the column (Ma et al., 2021).

2. RC Jacketing with Bent Bars

In this method, bent rebars with lengths nearly equal to the existing longitudinal reinforcement are mechanically or welded to the existing column bars. This type of jacketing is typically used for large cross-section columns where it is impractical to enclose the existing reinforcement with new stirrups. The use of bent bars creates effective bonding between the new RC layer and the old section, facilitating transfer of shear and tensile forces. This method is highly effective for strengthening large columns and ensures proper bonding between the new jacket and the existing structure (Ejaz, 2023).

10. Conclusion

Studies and analyses on structural behavior under seismic loading indicate that nonlinear methods, particularly pushover analysis and cyclic dynamic analysis, play a key role in achieving a more accurate understanding of structural performance and determining the actual load-bearing capacity. These methods, by precisely modeling the nonlinear behavior of materials and structural connections, allow for a more realistic simulation of structural responses under the cyclic loads generated by earthquakes. Nonlinear static analysis, despite its simplifications, can provide acceptable results for short- and mid-rise structures with vibration periods less than one second, provided that higher modes of vibration are considered. For taller structures with longer periods, accounting for higher modes becomes essential, as it improves the accuracy of behavioral predictions.

Furthermore, hysteresis curves obtained from cyclic analyses serve as important indicators for determining ductility, energy absorption capacity, and member durability under repeated seismic loads. Characteristics such as the area under the hysteresis curve, the number of stable cycles, and sensitivity to the nonlinear coefficient of materials are crucial factors in evaluating the actual performance of structures. In general, integrating nonlinear static and dynamic analyses with experimental data and numerical simulations provides a robust foundation for performance-based seismic design. This approach not only enhances life safety and reduces financial losses but also ensures reliable structural performance throughout the service life under various seismic scenarios. For this reason, the development and incorporation of such methods into seismic design codes and standards are of paramount importance.

In a broader summary of the topics discussed regarding steel structural design, it can be concluded that structural design is a scientific, engineering, and systematic process with the primary goal of ensuring safety, durability, and appropriate performance of structures under different loading conditions. This design is based on precise load analysis, an in-depth understanding of material behavior, proper selection of sections, compliance with code requirements, and the consideration of multiple design criteria.

The loads applied to a structure include permanent loads such as dead and live loads, and environmental or indirect loads such as wind, snow, seismic, and thermal loads. Each type of load has a specific influence on structural behavior and must be accurately calculated and combined. Dead loads consist of the self-weight of the structure and its fixed components, while live loads result from occupants, equipment, movement, and other variable factors. Snow and wind loads originate from climatic conditions and vary in intensity across regions, whereas seismic loads arise from ground motions and require precise seismic design measures.

In the design of steel members, the selection of section type plays a significant role in achieving strength and ductility. I-beams, channels, angles, T-sections, tubes, box sections, and composite sections are each applied according to specific structural functions. These sections must resist internal forces, including axial forces, shear forces, and bending moments, which arise from loading on various members. Steel, as a material, is valued in structural design for its high strength, uniformity, ductility, and recyclability. At the same time, its weaknesses—such as corrosion, poor performance at elevated temperatures, and susceptibility to brittle fracture—must be addressed through proper design measures, protective coatings, and quality control.

During the design process, engineers must consider criteria such as strength, stability, deformation, dynamic behavior, fatigue, and brittleness. These criteria determine whether the structure can remain safe and reliable throughout its service life under different loadings and environmental conditions. Each criterion, depending on the load nature, structural characteristics, and functional sensitivity, has its own analytical methods and design requirements.

All these processes must be aligned with reliable codes and standards such as the Iranian National Building Regulations, AISC, Iranian Seismic Code 2800, and international standards. Codes provide the necessary technical and legal framework for safe and economical design, ensuring harmony between structural design, execution, and operation. Ultimately, the design of steel structures combines science, experience, numerical analysis, engineering precision, and compliance with codes. Only through comprehensive adherence to technical principles, accurate understanding of real structural behavior, and detailed analysis of forces and materials can stable, safe, and durable structures be designed and built—structures capable of withstanding environmental and functional challenges.

Structures are subjected to a wide range of loads, which can be broadly divided into permanent and variable loads:

- **Dead loads**: These include the weight of structural and non-structural elements, acting permanently and continuously, and can usually be calculated with high accuracy.
- **Live loads**: These are variable, arising from occupants, equipment, and movement, and are often considered with higher safety factors.
- **Environmental loads**: These include wind, snow, and seismic forces, which are nonlinear and uncertain, requiring advanced modeling and dynamic analysis.
- **Seismic loads**: These are the most critical in seismic-prone areas and require specialized analyses based on seismic codes such as the Iranian Code 2800 or ASCE 7-22.

External loads applied to structures manifest internally as forces within members, namely:

- **Axial force (N)** along the member length (tension or compression)
- **Shear force (V)** perpendicular to the member
- **Bending moment (M)** causing flexural deformation
- **Torsional moment (T)** causing twisting around the longitudinal axis

Accurate analysis of these forces is performed using methods such as static analysis, matrix analysis, nonlinear analysis, and dynamic analysis.

Steel, as one of the most widely used materials in structural engineering, has advantages such as high strength, ductility, uniformity, ease of connection (bolting, welding, riveting), recyclability, and predictable engineering properties. However, disadvantages such as corrosion in humid environments, strength loss at high temperatures, fatigue sensitivity, and brittle fracture (particularly at low temperatures) must also be managed. These can be addressed with protective coatings, alloyed steels, rigorous quality control, and strict adherence to codes.

Each type of steel section is selected and designed based on the type and magnitude of internal forces (bending, axial, shear, torsional). For instance:

- Beams are usually designed with I- or H-sections.
- Columns often use built-up or box sections.
- Braces typically employ tubes or angles.
- Trusses often utilize angle or hollow box members.

In designing steel structures, multiple criteria are assessed simultaneously to evaluate structural behavior under different conditions:

- **Strength criterion**: Evaluates member resistance against maximum internal forces.
- **Stability criterion**: Controls global or local buckling.
- **Deformation criterion**: Ensures displacements and deflections remain within serviceability limits.
- **Dynamic behavior criterion**: Assesses response under seismic, wind, or impact loads.
- **Fatigue criterion**: Ensures resistance against repeated load cycles and prevents crack propagation.
- **Brittleness criterion**: Prevents sudden, warning-free fracture, particularly in connections and at low temperatures.

Authors' Contributions

Authors contributed equally to this article.

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In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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