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Conceptual design of transfer structures

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Abstract

A transfer structure (TS) is a structure that alters the load path of the gravity loads, shifting the line of thrust laterally to a different vertical alignment. Transfer structures are introduced in buildings that feature discontinuities in some columns or walls and where a direct load path to the foundations is not possible. They usually represent major elements of the structure and their impact on building cost and construction time can be substantial. This paper presents an overview of existing transfer systems and provides guidance on their design and construction. Extensive research on buildings with transfer structures all over the world was carried out (more than 100 examples were analyzed) with the aim of developing a rational typology of these structures. The results can be broken down into five main types: BEAM, TRUSS, INCLINED STRUT, PLATE, and ARCH & TIE.

KEYWORDS

construction, design, girder, transfer structure, truss

1 | INTRODUCTION

Functional, aesthetic, or planning needs predicate changes and discontinuities in the vertical load-bearing system of a building. These demands are often outside the boundaries of normal commercial development and create special and interesting engineering problems that are usually solved with some form of transfer structure.

Transfer structures provide a means of redirecting gravity loadings when a vertical supporting member has to be interrupted and a direct load path to the foundations is not possible. There are several reasons for which discontinuities in the supporting system are desired. For example, mixed-use high-rise buildings that provide for two or more types of occupancies require a different arrangement of the supporting structure for each functionality. In densely populated cities, large column-free spaces for lobbies or shopping areas are also required at the lower levels of tall buildings, and the construction almost invariably involves working within severe site constraints. Moreover, the unused spaces above existing activities and structures (air rights) have become attractive development sites in city centers and other areas where space is at a premium.

The position of the transfer structure in a building's elevation may be influenced by various factors such as architectural constraints, the location of the mechanical plants, and construction speed and economy. Low-level transfer structures simplify the construction process—they can be built using normal techniques and the superstructure is supported on the transfer structure right from the beginning. On the other hand, the construction of transfer structures at the top of the building or at intermediate levels usually requires significant temporary works. Transfer structures are usually composed of massive concrete or steel elements that occupy a lot of space and might not appropriately fit within a typical floor of a

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building. Therefore, it is usual to integrate these structures in the mechanical plant, making the least intrusion into usable spaces. Most modern tall buildings have sophisticated mechanical and electrical installations and, in general, the building is divided into several vertical zones, each served by its own mechanical plant. This means that the choice of the type and position of transfer structures throughout the building might not only be dictated by structural concerns but also has to be integrated with the building services.

The choice between a single-storey transfer structure and a multitier transfer system also depends on factors usually unrelated to structural efficiency. The position and number of mechanical plants, the construction method associated with each alternative, and even architectural preferences are often important issues that the engineer must take into account when conceiving the transfer system. For example, in the case of a multitier transfer structure, benefits may arise from the simultaneous construction on more than one floor, as each vertical zone (that is, a stack of floors supported on each transfer level) is independent of the others.

The possibilities for the configuration of the transfer structure are so wide that it may be positioned at a single level or, on the other hand, every floor can be part of the transfer system. Figure 1 illustrates this as (a) represents a building with a single-floor transfer structure at a low level, (b) shows the same building with two transfer floors, each transferring a set of storeys, and, in (c), the structural frame manages to gradually transfer the loads from all the floors to the supports.

In general, transfer structures should not participate in the lateral load-resisting system (as their function is to redirect gravity loads) but must maintain their load-carrying capacity through the full range of displacement that the building may be subjected to. Moreover, as transfer structures are very stiff elements of the structure, these will often attract considerable lateral loads and must be designed accordingly. Sometimes, it might make sense to combine the lateral stability system with the transfer structure. Most tall buildings require more than their central core to provide lateral stability when they reach the 40 to 50 storey range.[20] In such cases, a perimeter stability system can be integrated with the transfer structure to form a vertical Vierendeel frame or a braced façade.[26] Figure 1d–f shows examples of buildings where the braced façade—which has a major role in resisting lateral loadings—also manages to redirect the loads from the peripherical columns to the few supporting columns at ground level.

2 | TYPES OF TRANSFER STRUCTURES

The majority of transfer structures can be rationalized into five generic forms. These are the BEAM, TRUSS, INCLINED STRUT, PLATE, and ARCH & TIE, which are illustrated in simplified form in Figure 2. In most of these groups, all the three main structural materials—reinforced concrete (RC), prestressed concrete, and steel—may be considered, as well as composite schemes. The following sections introduce each type of transfer structure and describe its main features, as well as illustrate them through a set of representative examples.

2.1 | BEAM

For a wide variety of reasons, it is quite common that a column must be interrupted at a certain level and cannot go all the way to the foundations. The load arising from that column must be transferred to nearby ones by means of a transfer element that may be a beam. The term beam is generally applied to structural members subjected primarily to bending moments and shear forces. The most

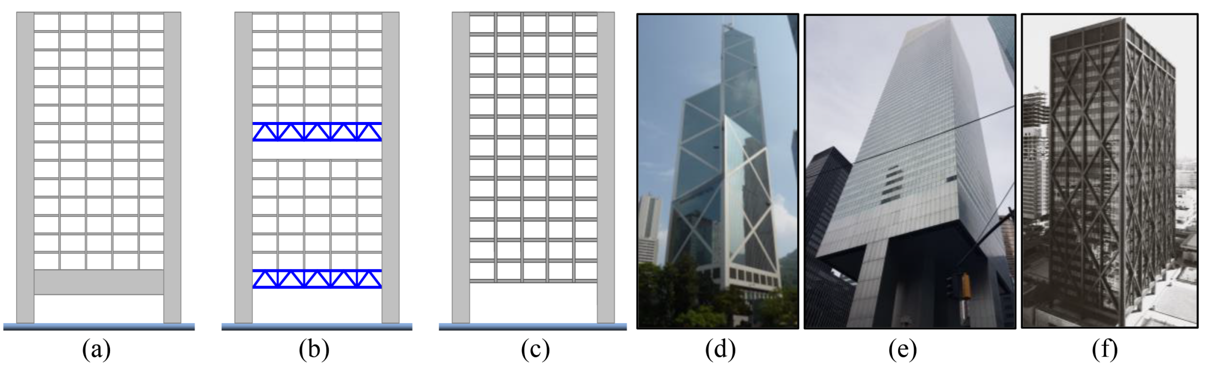


FIGURE 1 (a) Single-storey transfer structure; (b) multi-tier transfer structure; (c) structural frame transfer system; (d) Bank of China Tower, Hong Kong, China; (e) Citigroup Centre, Manhattan, New York, USA; (f) Alcoa Building, San Francisco, USA (*Source*: Google)

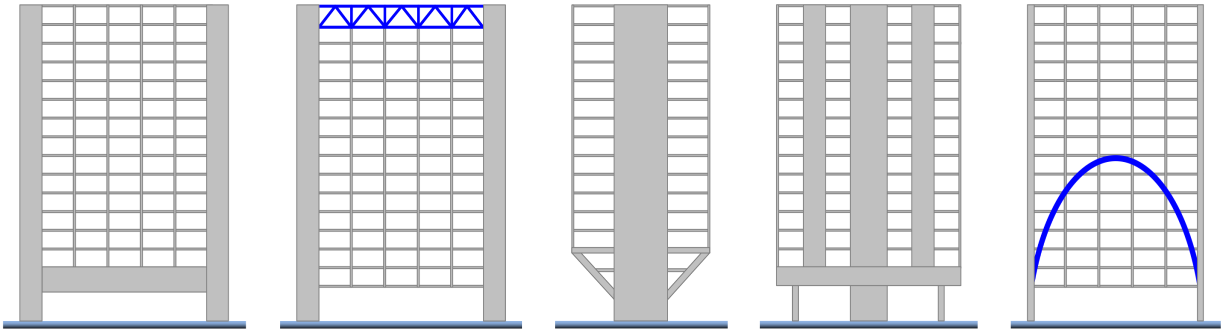


FIGURE 2 Types of transfer structures—BEAM, TRUSS, INCLINED STRUT, PLATE, and ARCH & TIE

FIGURE 3 (a) São Paulo Museum of Art, São Paulo, Brazil; (b) National Bank House, Melbourne, Australia[16]; (c) Four Pancras Square, London, UK; (d) Commerzbank Tower, Frankfurt, Germany (*Source*: [5,16])

common structural forms exhibiting beam behavior that are employed as transfer structures in buildings are transfer girders and Vierendeel frames.

Reinforced concrete transfer girders have been widely used due to their simple design and construction. They are usually employed to deal with local discontinuities in the supporting system but can also deliver radical changes in the structural grid. The major difference between a transfer girder and a common beam is that the former resists much larger loads. Hence, the main characteristic of a transfer girder is its unusual depth (Figure 3a,b). Due to the very large depths and substantial reinforcement quantities required for a reinforced concrete transfer beam, post-tensioning is usually employed as it is a very effective way to reduce both the depth and the reinforcement content.[8] Therefore, transfer beam elements are usually used as post-tensioned girders. The high strength of the prestressing steel compared to passive steel grades allows for a significant reduction of the cross-sectional area of reinforcement needed for flexion design. This, in turn, makes it possible to improve the detailing of the transfer element which can sometimes be a matter of concern. Prestressing also has the advantage of better controlling the deflections of the beam as it imposes upwards deformations.

The Vierendeel frame comprises horizontal top and bottom chords and vertical web members (Figure 3c,d). This design achieves stability through rigid connections between the members. Contrarily to the typical pin-connected truss, in which elements are only axially loaded, the members in a Vierendeel frame experience bending, shear, and axial forces.[22] The system is usually employed with reinforced concrete but can also be used with structural steel. A Vierendeel beam is heavier than an equivalent truss equally loaded so its popularity is not attributed to structural efficiency but rather to the architectural and mechanical integration that the system provides. The absence of diagonals makes it suitable for storey-height construction without significant obstruction to openings.

2.2 | TRUSS

Trusses are lighter in self-weight than concrete girders and can transfer loads over large spans. They are used in a broad range of structures and can also be found acting as transfer structures in buildings. As trusses are open web structures, this system provides better integration with architecture and mechanical systems than an equivalent transfer girder. In fact, by increasing the truss depth to a certain number of floors, its members become so slim that they can be integrated into typical residential or office layouts. That is a major advantage of this type of transfer structure as the value of the net internal areas far outweighs the differences in the cost of the structure.

There are two main types of transfer system where the truss concept is applied: the transfer truss and the hanger. The first is a normal truss, usually spanning between RC walls or columns, and receiving load from the discontinued columns at node locations, as illustrated in Figure 4. The hanger transfer structure, on the other hand, is also composed of axially loaded members but it is a simplification of a normal truss, as it is only composed of an inclined member in tension and a bottom horizontal element in compression (Figure 5). The clear distinction between these two transfer structures was motivated by the differences in the complexity of the systems, the materials used, and the types of connections and design procedures involved.

2.3 | INCLINED STRUT

The inclined strut is a transfer system that gradually migrates vertical load from the application point to the supports. It can appear in the form of an inclined column, a walking column, and a wall or a deep beam. Inclined columns may be made of structural steel, reinforced concrete, or composite systems, whereas walking columns and deep beams are always concrete elements.

Adopting inclined columns is a way of transferring vertical load from one column location above to a different support location below. The eccentricity of the transferred load causes an out-of-balance moment that cannot be neglected, and, therefore, in order for the system to be in static equilibrium, a set of horizontal forces are required. This system can be applied to attain a small adjustment in the column locations, stepping the column positions incrementally over a number of floors to

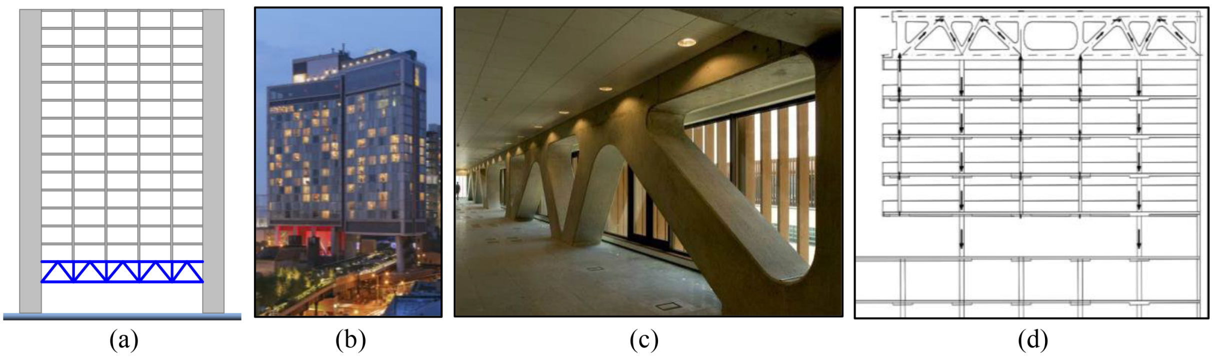


FIGURE 4 (a) Transfer truss scheme; (b) The Standard Hotel, New York, USA; (c) Art's Business & Hotel Centre, Lisbon, Portugal; (d) gravity loads path through the transfer truss in the Art's Business & Hotel Centre (*Source*: [2], Google)

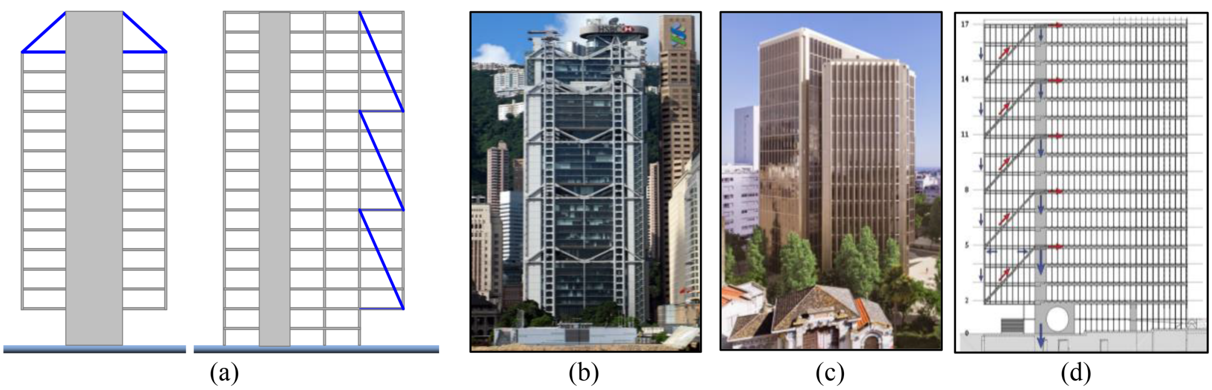


FIGURE 5 (a) Hanger TS (two possible arrangements); (b) HSBC Main Building, Hong Kong, China; (c) FPM 41 Building, Lisbon, Portugal; (d) gravity loads path through the hanger transfer structure in FPM 41 Building (*Source*: [3], Google)

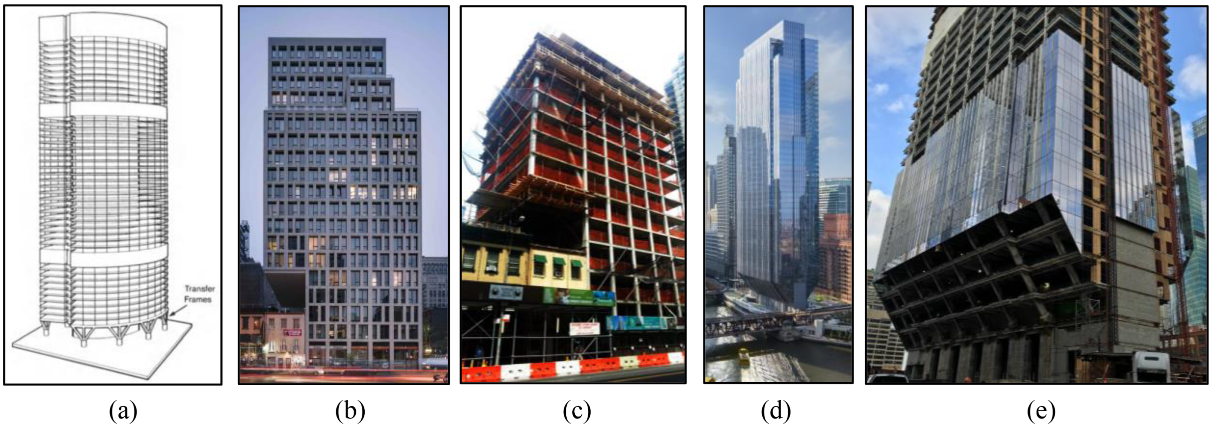


FIGURE 6 (a) Structural system of the Grosvenor Place, Sydney, Australia; (b) 160 East 22nd Street Building, Manhattan, New York, USA; (c) inclined column view during construction of the 160 East 22nd Street Building; (d) 150 North Riverside Plaza, Chicago, USA; (e) inclined columns of the 150 North Riverside Plaza (*Source*: Google)

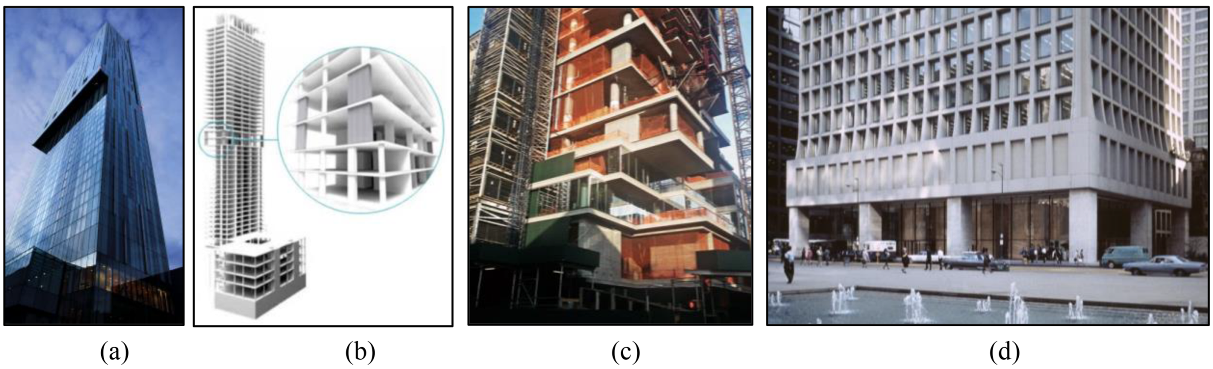


FIGURE 7 (a) Beetham Tower, Manchester, UK; (b) walking column system at the Beetham Tower; (c) walking column at the 56 Leonard, Manhattan, New York, USA; (d) deep beam in the Brunswick Building, Chicago, USA (*Source*: Google)

achieve the overall desired offset, or to undertake major transfers (Figure 6), being a critical element of the whole building structure. In the first case, the lateral forces induced by the load eccentricity can often be resisted by tension and compression of the slabs at floor levels, and the system relies on the diaphragm action of the latter to distribute the lateral forces to the shear walls. In the second case, a specific structure to deal with the pull and push forces generated is usually required.

A walking column is a tied-back shear panel transfer system in which the vertical load is shifted laterally by means of a vertical concrete wall loaded essentially in shear (Figure 7a,b). A tie at the top of the panel and a compression strut at the bottom (or vice versa), both connected to the building's main lateral load-resisting system, restrain the moment induced by the eccentricity of the gravity loads. This structural system is completely equivalent to that of an inclined column since the inclined strut, similar to the inclined column, is developed within the concrete wall. This design is widely applied to achieve small adjustments in column location, as shown in Figure 7c.

Finally, a deep beam is characterized by having a relatively small span-to-depth ratio, generally below 3–4.[19] It has a shear dominant behavior instead of a flexural dominant one, characteristic of normal beams. Deep beams are widely used as local transfer structures to interrupt a single column, however, they may also be employed to redirect load from several columns, as illustrated in Figure 7d. Contrarily to the inclined column and walking column schemes, this system does not rely on external elements to achieve stability.

2.4 | PLATE

A plate is a three-dimensional solid whose thickness is very small in comparison with the other dimensions, and it is characterized by receiving load only transversely to its plane. The plate concept can be employed to create a transfer structure that takes the form of a reinforced concrete transfer plate or a transfer grid. Transfer structures are used when an adjustment in the structural layout of the building is required, and particularly in the cases of transfer plates or grids, the supporting system may change significantly from the upper structure to the podium.

A transfer plate is a thick reinforced concrete slab that can redirect loads in more than one direction and, therefore, is particularly suitable when a radical change in the building grid is required. This solution provides great flexibility to the architect and the structural engineer to modify the supporting system and the vertical load path. In high-rise buildings, the transfer plate is usually placed between the tower and the podium, 20–30 m above ground level. The upper structure often accommodates offices or residential units whereas the podium floors house other functional spaces such as a shopping mall or a lift lobby, which require large column-free areas. Buildings with a transfer plate are usually composed of a shear wall system in the upper structure, mega-columns below the transfer floor, and the only continuous vertical element is a central core. Therefore, the transfer plate admittedly participates in the lateral load-resisting system, as some of the transferred members may attract significant lateral loads.

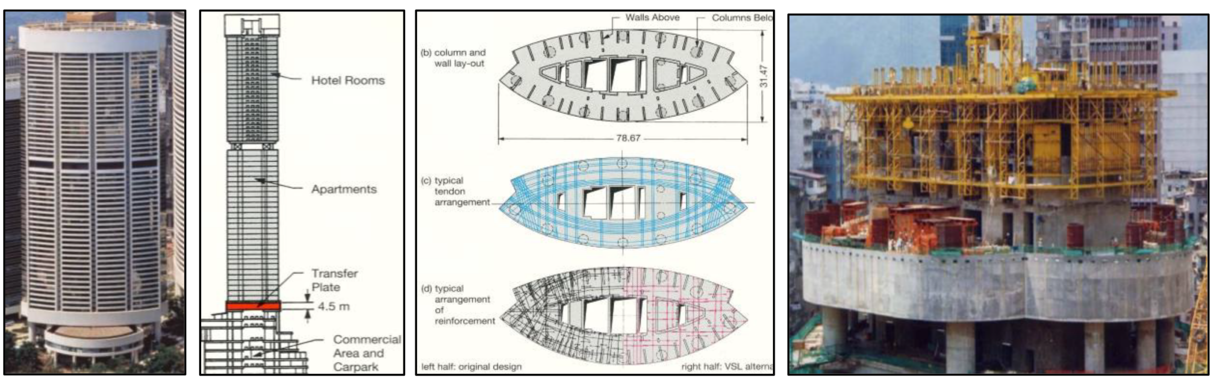
As the transfer plate usually extends the entire building footprint and has a thickness of up to several meters, it is a massive concrete structure with substantial self-weight and large amounts of reinforcement, as illustrated in Figure 8. Post-tensioning of the transfer plate is an effective way of reducing the reinforcement quantities and the plate thickness and improving the cracking and deflection behavior.[21] The reduction of the plate thickness, and thus of its self-weight, is also advantageous for the falsework system which has to support a lighter structure.

The transfer grid (Figure 9) is a variant of the transfer plate system. Instead of being a continuum concrete slab, it consists of an assembly of reinforced concrete beams, usually in two orthogonal directions. While the transfer plate can redirect loads in virtually any direction, the grid system is not so versatile as it is restrained to beam directions.[1] However, the transfer grid has the following advantages over the transfer plate: it provides free space between the beams that often accommodates mechanical or electric installations; its structural behavior is clearer and easier to model; and it is a lighter structure, which has direct implications for the design of the falsework system. The beams are usually prestressed to reduce depth and reinforcement quantities.

2.5 | ARCH & TIE

The arch and tie structural systems are commonly used due to their efficiency, reduced self-weight, long-span capability, and ability to withstand lateral movement. This type of structure is usually required to span long distances and does not need to hold significant loads, unlike in general buildings. However, although it is not common to see arches and suspension systems in buildings, these elements can, in fact, be used as transfer structures. Figure 10a,b presents two examples where the arch transfer system was employed, representing a defining feature of the buildings. Likewise, Figure 10c shows a building where the tie element was applied as a transfer structure, which may be referred to as a suspension system.

Reactive forces will develop at the arch or tie ends, which have both vertical and horizontal components. A basic design issue is whether to support the horizontal thrust involved directly through the foundations or to use a supplementary horizontal compression strut in the case of the tie or a tie-rod in the case of the arch. Designing



(a) (b) (c) (d)

FIGURE 8 (a) The Pacific Place, Hong Kong, China; (b) structural system of the Pacific Place; (c) Pacific place's transfer place layout and detailing; (d) Langham Place's transfer plate, Hong Kong, China (*Source*: [14,21])

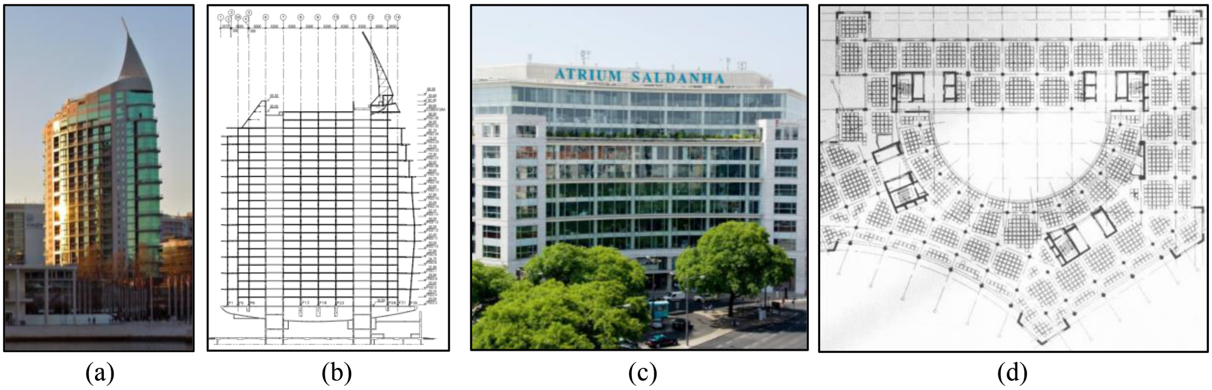


FIGURE 9 (a) Saint Gabriel Tower in Lisbon, Portugal; (b) Saint Gabriel Tower structural system[1]; (c) Atrium Saldanha Building; (d) Atrium Saldanha floor layout (*Source*: [1,27])

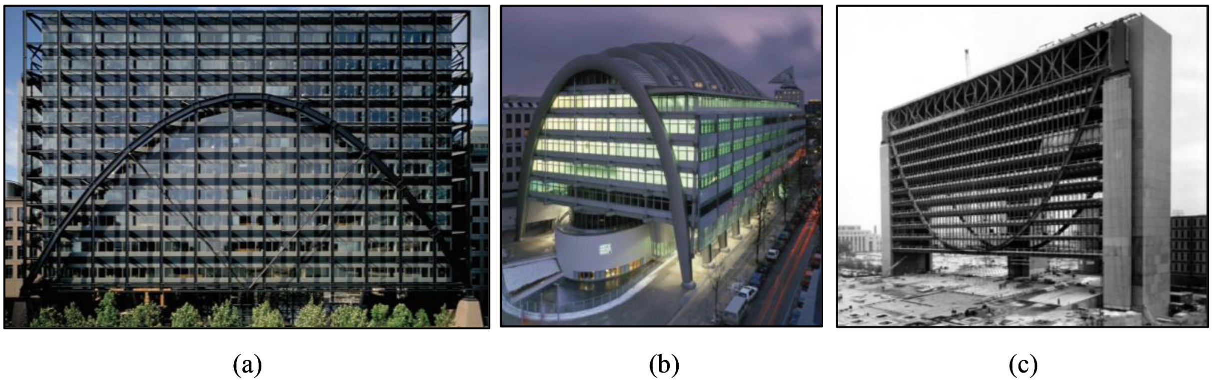


FIGURE 10 (a) Broadgate Exchange House, London, UK; (b) Ludwig Erhard Haus, Berlin, Germany; (c) Marquette Plaza, Minneapolis, Minnesota, USA (*Source*: [11–13])

the foundations to absorb both vertical and horizontal thrusts may not be practical due to the significant horizontal forces involved; hence, this solution is rarely used. In most cases, the horizontal thrusts are then resisted by compression struts or tie-rods.

3 | KEY CONSIDERATIONS ABOUT THE STRUCTURAL DESIGN OF TRANSFER STRUCTURES

3.1 | Serviceability requirements

The deformation of a transfer structure must be carefully assessed since a large part of the building (and sometimes the whole building) depends on it. As a guiding principle, a transfer structure should ideally lead to deflections similar to those that would occur if the vertical elements were continuous (or, in other words, if there was no transfer structure). This may be achieved using post-tensioning, but in most cases, the transfer structure will deflect, and deflection criteria must be settled. In general, building codes refer span/250 as an appropriate limit value for the vertical deflections of beams and slabs, for the quasi-permanent loads.[6] Furthermore, span/500 is normally an adequate limit for deflection after construction, meaning the deflection which occurs after the addition of partition and finishes. Currently, there is not much guidance as to the deflection limits for transfer structures, although it is commonly accepted that their design should follow more severe criteria than normal beam or slab elements. This can be achieved either by imposing stricter limits or by designing for a more severe load combination, such as frequent loads or characteristic loads. Despite this, the serviceability criteria for global transfer structures must be specified for each project and agreed with the client.

Additionally, dynamic effects must be considered in any structure to ensure that vibrations do not impair the comfort of the users or the functioning of the structural members. The great variability in vertical stiffness and mobilized mass makes some transfer structures extremely susceptible to vertical excitations. Therefore, the effects of human-induced vibrations must be controlled, and the vertical component of the seismic action gains additional importance, which is not common in building structures.[24] In the first approach, vibration control can be achieved by ensuring that the frequencies of the natural modes of vibration are kept above or below appropriate levels, which depend on the function of the structure and the source of vibration. Possible sources of vibration include walking, synchronized movements of people, ground-borne vibrations from traffic, and wind action. When a structure is subjected mainly to pedestrian traffic, 5 Hz is often assumed as the minimum frequency of the vertical mode of vibration of a floor structure to ensure satisfactory behavior.[10] However, if the frequency of the vertical mode of vibration is indeed below 5 Hz, this does not imply that problems will arise regarding users' comfort. In this case, an appropriate analysis must be carried out to explicitly assess the effects of human-induced vibrations. This analysis will often involve modeling human action (such as walking or synchronized jumping) and the measurement of vertical accelerations or other related parameters.[24]

3.2 | Deflection compatibility

The long-term differential shortening between the supporting elements of a transfer structure may be regarded as a support settlement from the perspective of the transfer structure. In tall buildings, long-term differential shortening may result in distortion of the horizontal elements and cracking in non-structural elements. This phenomenon is even more serious for transfer structures, as these usually possess large flexural stiffness. Thus, the design of the transfer structure must include the effects of differential shortening between the supporting elements, when these are found to be significant. Both elastic shortening and the shortening due to creep and shrinkage should be accounted for. If not specifically mitigated, the imposed forces and bending moments due to this differential settlement can become very large, especially in high-rise buildings. Since designing the transfer members and connections for these additional anticipated forces is a considerable penalty, minimizing the effect through the adequate conceptual design of the solution (regarding the sizing of the TS supporting elements), proportioning (relative stiffness of the TS), construction sequencing, special detailing, or other methods is a worthwhile effort.[7] Construction techniques such as floor-by-floor construction and construction schedules have a substantial influence on the amount of differential shortening.[9]

Additionally, the support that a transfer member provides is not as stiff as a regular column. In other words, the flexural stiffness of a suitable transfer beam or truss for a given situation is much lower than the axial stiffness of a concrete column, for example. This condition should be properly addressed during the analysis and design of the structural members above the transfer level. The deflections of the transfer structure will lead to a redistribution of loads on the upper structure of the building. Therefore, allowance should be made in the design of the supported structure for the deflection of the supporting members. This will normally involve the design for settling supports and may require continuous bottom reinforcement at transferred columns. As for the analysis of the upper floors, care should be taken if the structural model above the transfer structure is analyzed separately with the assumption that the supports offered by the transfer structure are rigid. If the deflections of the transfer structures are found to be significant, the load redistribution should be carefully examined. In addition, staged construction analyses should be carried out to correctly assess the differential settlements of these "softer" columns in order to adequately reinforce the slabs.

3.3 | Seismic action and design

The conceptual design of buildings with global transfer structures in seismic regions must be carefully planned and ensure that the transfer structure does not jeopardize or impair the seismic design of the building. This can be achieved providing that the transferred elements are completely secondary, meaning that their contribution to resisting the seismic loading is negligible. Ideally, the lateral load resisting system should be practically the same above and below the transfer structure, as all the primary elements must be continuous in elevation and the transferred elements are secondary. The discontinued elements should provide only vertical support and have insignificant lateral stiffness and shear and flexure resistance. Notwithstanding, these elements and their connections must be designed and detailed with appropriate ductility to maintain their load-bearing capacity under the displacements imposed by the seismic action.

Given that the discontinued vertical elements should not have any relevant shear capacity, the transfer structure itself should not participate in the seismic resisting system by transferring lateral load. However, there are situations where the interaction between the transfer structure and the primary supporting elements does play a role in resisting lateral loads. This is the case, for example, when a very stiff transfer structure spans between two primary vertical elements with fixed supports, creating a frame behavior, as illustrated in Figure 11a. Likewise, Figure 11b shows the outrigger effect that the

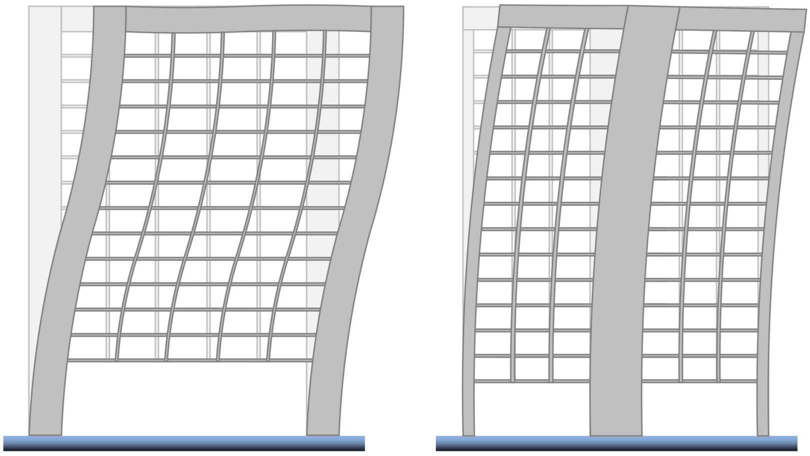


FIGURE 11 Examples of structural systems of buildings with transfer structures not covered by codes; (a) frame effect; (b) outrigger effect

transfer structure may also induce by engaging a central core with the perimeter columns. If a building has several transfer levels along its height, it is possible to take advantage of the former effects, as the primary vertical elements and the transfer structures work together to form a vertical Vierendeel frame or a multiple-level outrigger system, respectively.

Soft-storey seismic provisions in building codes limit the permissible variation in stiffness or strength from storey to storey. The use of global TSs in buildings may result in the creation of soft-storey mechanisms because the transfer level is in general significantly more stiff and stronger than the storey below.[25] This apparent contradiction is solved through an adequate conceptual design of the whole building. In fact, the mentioned code requirements are intended to avoid a uniformly stiff or strong structure having a soft or weak storey, where deformations would concentrate resulting in an early collapse of the building under the seismic event. However, transfer structures should create the opposite situation: a uniformly stiff or strong building that is additionally stiffened and strengthened at the transfer level. That is achieved by providing that the transfer structure is connected to at least one primary vertical member that provides the majority of the inter-storey stiffness.

In addition, prescriptive code seismic requirements of strong column-weak beam are intended to avoid the undesirable phenomenon of all columns in a storey yielding and developing hinges at top and bottom, potentially leading to storey collapse. In a building with a transfer structure, the strong column-weak beam provision does not appear necessary or appropriate at the transferred elements because the primary uninterrupted elements already provide a continuous strong spine desirable for favorable seismic performance. The strong column-weak beam philosophy should apply only considering the strong primary elements as the columns and the transfer structure as the beam, checking that the transfer structure does not develop forces large enough to cause the failure of the primary elements under the seismic event. Therefore, the discontinued vertical elements may develop plastic hinges at the top or bottom of the transfer level, but storey collapse cannot occur as long as the primary elements are standing.

Regarding the seismic design of the transfer structure, in general, seismic design according to codes is based on elastic analysis methods using global force reduction factors to address buildings with distributed stiffness and strength. However, current codes do not cover all structural types, and buildings incorporating global TSs often present structural systems that do not fit in any of the categories prescribed, as illustrated in Figure 11. In fact, in such buildings, different structural elements of the lateral-load resisting system might have very different ductility capacities and demands. For example, coupling beams between RC walls may experience high demand from storey shears and require high ductility, while transfer structures are usually designed to remain elastic under the largest seismic event required by codes. The choice of the force reduction factor for use in an elastic analysis must be adequately defined and justified. However, there may not be any rational and defensible way to derive such a factor for a given building. In fact, regarding high-rise or complex structures, it is simply not appropriate to design the building for the elastic seismic load effects reduced by a global force reduction factor, as this method cannot predict, either accurately or conservatively, force, drift and acceleration responses in building frame systems that undergo significant inelastic action.[23] For tall buildings, minimum base shear is typically greater than shear determined by linear elastic response spectrum analysis. As a result, the effective force reduction factor in prescriptive design should be lower than the value indicated in the building code for that structural system.[15] Therefore, code prescriptive design procedures may not be appropriate for complex structural systems. Non-linear time-history analyses as part of a Performance-Based Design approach are recommended, which can demonstrate adequate behavior of the transfer structure by showing it remains elastic even under large seismic events.[7] As an alternative, the capacity design philosophy may be applied to the design of the transfer structure to ensure elastic behavior under all seismic loadings.

3.4 | Robustness and disproportionate collapse

Transfer structures are often regarded as critical elements for the overall stability of the building. As global TSs are major elements of the structure and play such a big role in the vertical load-bearing system, considerations of robustness and disproportionate collapse are key to their design. The resistance to disproportionate collapse is achieved through providing the structure with adequate robustness, designing it to be able to redistribute load when a load-bearing member suffers a loss of strength or stiffness and to have ductile global failure modes, rather than brittle ones. There are four basic approaches to design for robustness in structural engineering, which are common to all the codes around the world[4]: (i) tie-force based methods; (ii) alternate load path methods; (iii) key element design; and (iv) risk-based methods.

Building structures are generally categorized into the four risk classes (Classes 1, 2A, 2B and 3), and for each of these classes, design criteria for meeting the robustness requirements are prescribed in codes.[4] Large transfer structures such as concrete plates, grids, or steel trusses are usually present in tall buildings, which are classified as Class 3. The design for the robustness of buildings with global transfer structures will often involve a systematic risk assessment of the structure, as recommended for Class 3 buildings. However, there is little practical guidance available on the expectations for risk-based methods. Notwithstanding, as a minimum requirement, buildings with transfer structures should be no less robust than Class 2B buildings, and the alternative load path and key element design methods should be applied. The alternative load path methods are always preferable over the key element design and should always be prioritized in dealing with disproportionate collapse.[4] For example, Figure 12 illustrates the application of the alternative load path method through four scenarios involving the sudden failure of different critical members, and Figure 13 showcases some of the results obtained in terms of axial force and vertical displacements of key members for selected scenarios. However, since transfer structures are often single elements, the notional removal approach is unlikely to be a viable design strategy in many cases. Thus, the design of transfer structures and, as importantly, of their supports, may be based on the key element design. It should be stressed that the key element design as prescribed by codes might be insufficient, and transfer members that are vital to the stability of a large part of the structure should be designed for the loads arising from all normal and abnormal hazards, as predicted through a comprehensive risk assessment.

3.5 | Construction sequence

The structural behavior of a building, comprising its response in terms of movements, variations in internal

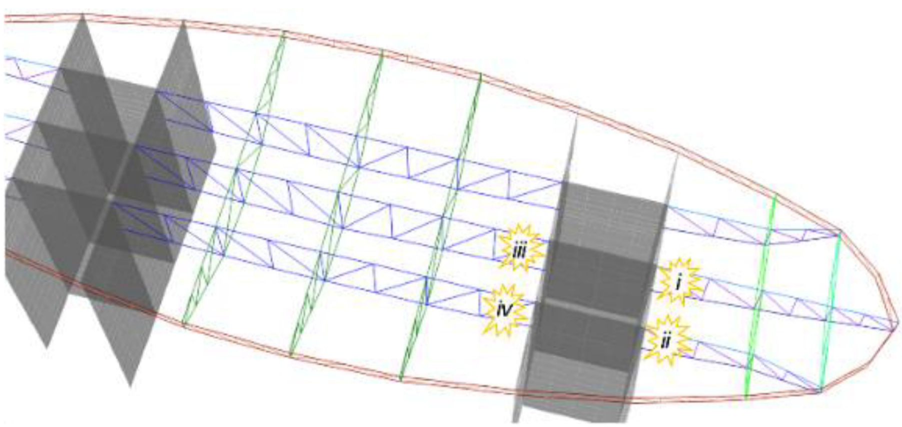


FIGURE 12 Illustrative representation of scenarios considered in a disproportionate collapse analysis: (i) failure of upper chord, lower chord, and diagonal of the central longitudinal truss in the cantilever area (ii) failure of upper chord, lower chord, and diagonal of the lateral longitudinal truss in the cantilever area; (iii) failure of upper chord, lower chord, and diagonal of the central longitudinal truss in the central span area; (iv) failure of upper chord, lower chord, and diagonal of the lateral longitudinal truss in the central span area

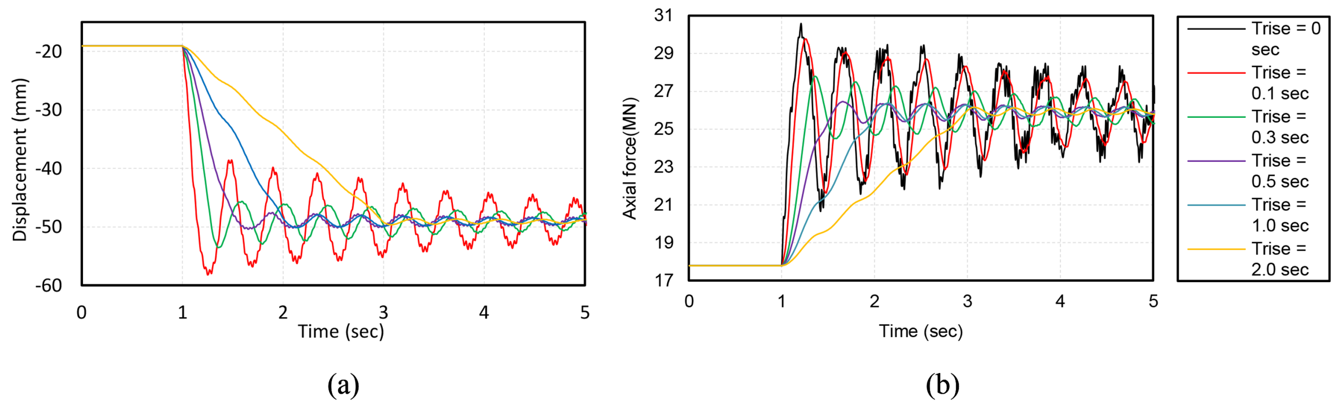


FIGURE 13 (a) Time-history of the vertical displacement of the elements adjacent to the failure when scenario (iv) occurs; (b) time-history of the axial force in the diagonal of the central longitudinal truss adjacent to the core, in zone 1, when scenario (iv) occurs

forces, moments and stress distributions, and development of locked-in forces will gradually change during and after the construction due to varying loading conditions and time-dependent properties of the materials such as concrete creep, shrinkage and aging, and tendon relaxation. Therefore, especially in tall buildings, it is highly recommended that a construction-staged analysis is performed to accurately estimate the final geometry of the building and the forces the elements must resist at each stage of construction. The effects of the construction sequence may be extremely important for the design of transfer structures due to the comparatively large stiffness of these elements and the sequential built-up of stiffness of structural framework above the transfer level.[10] Only through a staged construction analysis will the load transfer history be correctly incorporated into the design of a transfer structure.

A comparative study between a staged construction analysis and a conventional lumped analysis[17] based on a 25-storey building with low-level transfer beams estimated that sequential analysis leads to increments of about 30% in both the deflections and the bending moments and shear forces on the transfer beams. This conclusion shows that the effects of the construction sequence cannot be neglected and demonstrates the importance of performing a staged construction analysis.

4 | CONCLUDING REMARKS

Extensive research on buildings with transfer structures all over the world has been performed. Based on more than 100 examples that were analyzed,[18] a rational typology of existing transfer structures was developed based on their structural system, and the following conclusions may be drawn.

Regarding the materials employed, any type of transfer structure can be materialized with either concrete or steel, although there appears to be a preference for a certain material in each type, as demonstrated in Figure 14. For example, transfer structures within the BEAM, INCLINED STRUT, and PLATE types are mostly made of concrete or prestressed concrete, whereas structural steel is more popular for the TRUSS and ARCH & TIE types.

This is related to the structural behavior of each transfer system, since concrete is clearly predominant in flexion or shear-dominant structures (BEAM and PLATE), and steel is preferable for axially loaded elements (TRUSS and ARCH). It is interesting to note that, within the TRUSS and ARCH & TIE types, composite steel and concrete solutions are quite common, contrarily to the other types of transfer structures, in which one material seems to be dominant.

The evolution of transfer structures over time is represented in Figure 15. From the analysis of this figure, it is noteworthy that some types of transfer structures were more popular in past decades and others are currently more widely employed. For example, most of the buildings within the BEAM type were built in the 1960s and 1970s and there is only one representative example from recent years. In contrast, buildings using the TRUSS system are increasingly more common, and the majority of the examples shown are subsequent to 1990. Examples of the ARCH & TIE type are relatively scarce, but there is no recent application of this system, and the INCLINED STRUT and PLATE types do not appear to be more common in any specific time period. It is clear that the ARCH & TIE schemes are particularly suitable to achieve long-span transfers. Furthermore, the overall most common type of transfer structure is the TRUSS and, judging by the past two decades, it seems that this scheme is going to prevail over the other types of transfer structures in the near future, and reaching for bigger spans.

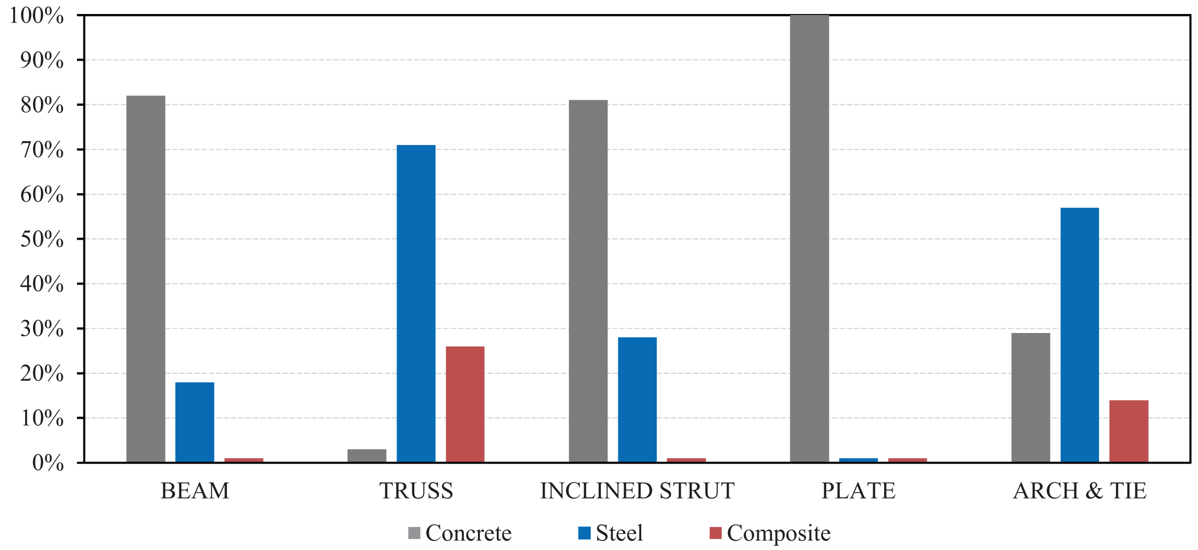


FIGURE 14 Materials employed in each type of transfer structure

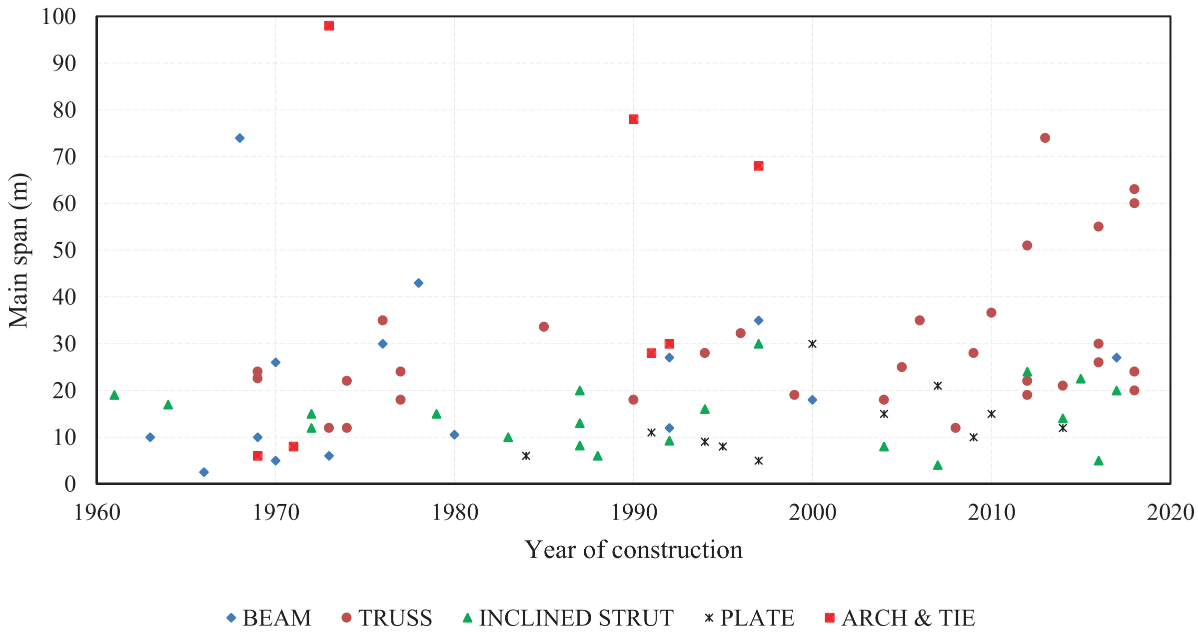


FIGURE 15 Year of construction and main span for buildings with global transfer structures (for cantilevered TSs, the adopted span was twice the cantilever length for a better comparison with normal span TSs)

In conclusion, transfer structures provide a means of redirecting gravity loadings when a vertical supporting member has to be interrupted and a direct load path to the foundations is not possible. The need for TSs is evident, as adjustments in the structural grid are required for the most varied reasons, and the combination of several functionalities in the same building is increasingly more common. Discontinued vertical members often create unusual engineering and construction challenges (e.g., logistical challenges related to sequencing, erection of heavy elements, as well as formwork complications), and it is up to the structural engineer to conceive a transfer solution to provide the vertical support needed. The choice of transfer structure and the material employed is ultimately dictated by several factors such as design requirements, the building's needs, industry know-how, market rates and conditions, and construction considerations. Thus, transfer structures may exist under virtually any form, the only limit being the designer's creativity. This paper presents a review of the principal structural systems employed as TSs in buildings and provides an overview of technical background information necessary to understand and address key issues associated with transfer systems use.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

1. Almeida J, Appleton J, Abecassi T, Silva JN, Câmara JN. Structural system of the Saint Gabriel and Saint Rafael towers; 2001.
2. Almeida J, Lourenço M. Estrutura do Art's Center. Encontro Nacional Betão Estrutural. 2004;2:1251–8. Faculdade de Engenharia da Universidade do Porto, Porto (in portuguese).
3. Almeida J, Lourenço M, Camara J. Edifício FPM41. Encontro Nacional Betão Estrutural. Lisboa: LNEC; 2018 (in portuguese).
4. ARUP. Review of international research on structural robustness and disproportionate collapse; 2011.
5. Campagnol G, Caffey S. Construction of the Museu de Arte de São Paulo; 2015.
6. CEN. EN 1998-1: Eurocode 8: Design of structures for earthquake resistance -Part 1: General rules, seismic action and rules for buildings; 2004.
7. CTBUH. Outrigger Design for High-Rise Buildings. Chicago: Council on Tall Buildngs and Hurban Habitat (CTBUH); 2012.
8. fib. Post-tensioning in buildings. International Federation for Structural Concrete; 2005.
9. fib. Tall buildings: structural design of concrete buildings up to 300m tall; 2014.
10. Gilbert R, Mickleborough N, Ranzi G. Design of Prestressed Concrete to AS3600-2009. CRC Press; 2015.
11. Gregull T. Design and Construction of the Ludwig-Erhard-Haus.
12. Iyengar H, Baker WF, Sinn RC. Broadgate exchange house: structural systems; 1993.
13. Li Q, Huo P, Shu S, Chen D, Duan Y, Nie T. The Federal Reserve Bank of Minneapolis (Marquette Plaza).
14. Man RW. Construction of Langham Place.
15. Moehle JP. The tall building iniciative for alternative seismic design; 2007.
16. Nutt J, Haworth P. Capital tower. ARUP J. 1976;27–32.
17. Pranay R, Sreevalli IY, Kumar ETS. Study and comparison of construction sequence analysis with conventional lumped analysis using Etabs.
18. Ribeiro G. Structural design of transfer structures. Instituto Superior Técnico, University of Lisbon (MSc thesis); 2018.
19. Taranath B. Deep Beams. Reinforced concrete design of tall buildings. CRC Press; 2010. p. 83–5.
20. Taranath B. Structural analysis and Design of Tall Buildings. McGraw-Hill, Inc; 2011.
21. VSL. Post-tensioned in buildings. Ltd: VSL International; 1992.
22. Wickersheimer D. The Vierendeel. J Soc Archit Hist. 1976; 36(1):54–60.
23. Willford M, Whittaker A, Klemencic R. Recommendations for the seismic design of high-rise buildings; 2008.
24. Willford M, Young P. A design guide for footfall induced vibrations in structures. The Concrete Society; 2006.
25. Zhou Y, Chen P, Wang C, Zhang L, Lu L. Seismic performance evaluation of tall, multitower reinforced concrete buildings with large bottom podiums; 2018.
26. Zunz J, Wise C. Transfer Structures. Second Century of the Skyscraper. 1988;367–82.
27. Trigo Lda T. The Atrium Saldanha Building. Estruturas de Betão em Portugal. Período de 1994 a 1998; 1998.

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