Structural design of transfer structures

Dimensionamento de estruturas de transição

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Abstract

A transfer structure 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 vertical elements and where a direct load path to the foundations is not possible. This paper presents an overview of existing transfer systems and provides guidance on their design and construction. Extensive research on buildings with transfer structures was carried out 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 & CABLE. In addition, transfer structures' design is often outside the scope of normal code guidance and may require a degree of engineering judgment. This paper also highlights the key aspects that determine the structural design of transfer structures, as well as typical construction methods.

Resumo

Uma estrutura de transição (ET) é uma estrutura que altera o caminho-de-carga das forças gravíticas. ETs são inseridas em edifícios que exibem descontinuidades em pilares ou paredes resistentes, e onde um caminho-de-carga direto para as fundações não é possível. Estas estruturas constituem elementos condicionantes do edifício onde se inserem, e o seu impacto no custo e no tempo de construção pode ser significativo. Este documento apresenta uma perspetiva geral das estruturas de transição existentes em edifícios e reúne princípios orientadores para o seu dimensionamento e construção. Foi realizada uma extensa pesquisa sobre edifícios com ETs em todo o mundo com o objetivo de desenvolver uma tipificação adequada destas estruturas. O resultado consiste em cinco tipos principais: VIGA, TRELIÇA, ESCORA INCLINADA, PLACA E ARCO & CABO.

Keywords: Transfer structure / Girder / Truss / Plate / Design / Construction

Palavras-chave: Estrutura de transição / Viga de transição / Treliça de transição / / Laje de transição / Dimensionamento / Construção

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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 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 with structural efficiency. The position and number of the 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

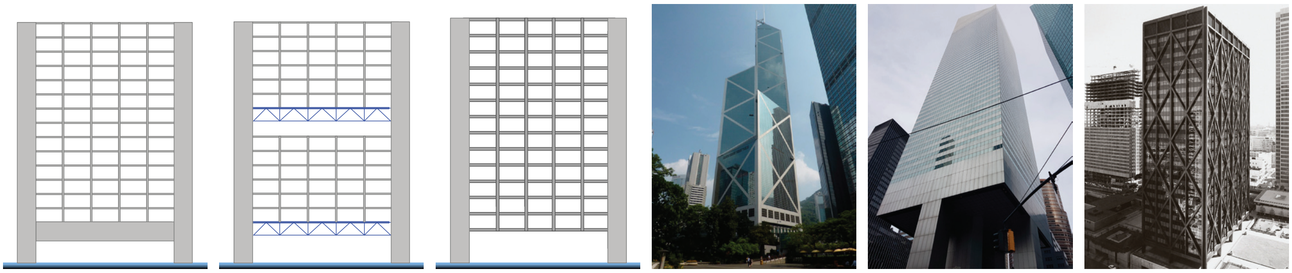


Figure 1 (a) Single-storey TS; (b) Multi-tier TS; (c) Structural frame transfer system; (d) Bank of China Tower, Hong Kong, China; (e) Citigroup Centre, Manhattan, New York, USA; (f) Alcoa Building, San Francisco, USA

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 [1]. In such cases, a perimeter stability system can be integrated with the transfer structure to form a vertical Vierendeel frame or a braced façade [2]. Figures 1d, 1e and 1f show 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 the transfer structures can be rationalized into five generic forms. These are the BEAM, TRUSS, INCLINED STRUT, PLATE, and ARCH & CABLE, 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 has to 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 stresses and also to shear stresses. The most common structural forms exhibiting beam behavior that are employed as transfer structures in buildings are transfer girders and Vierendeel frames.

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 (Figures 3a and 3b). Due to the very large depths and substantial reinforcement quantities required for a reinforced

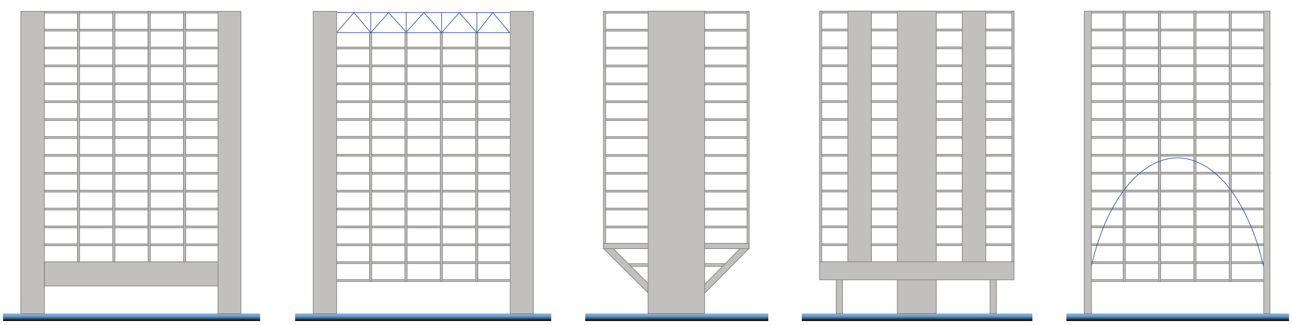


Figure 2 Types of transfer structures – BEAM, TRUSS, INCLINED STRUT, PLATE, and ARCH & CABLE

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

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

concrete transfer beam, post-tensioning is usually employed as it is a very effective way to reduce both the depth and the reinforcement content [3]. 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 (Figures 3c and 3d). 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 [4]. The system can be employed both in concrete and in 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 a 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 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

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

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 [6]

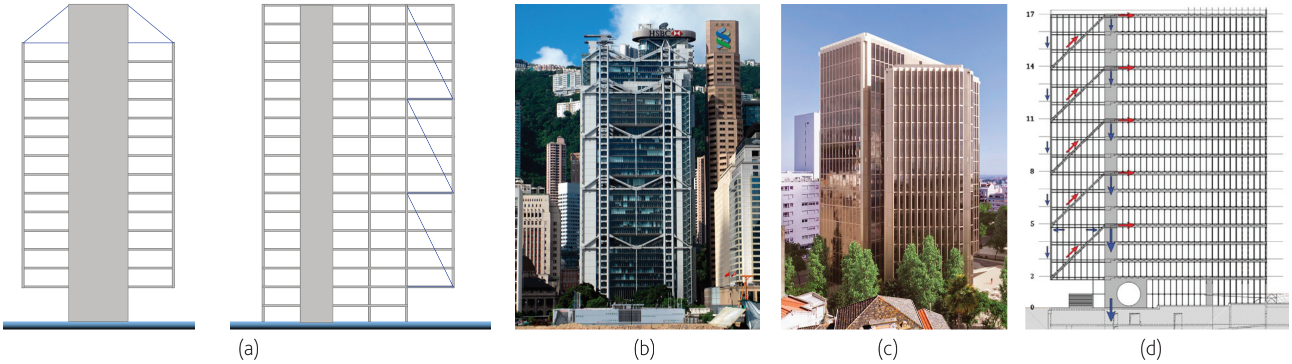


Figure 5 (a) Hanger TS (two possible arrangements); (b) HSBC Main Building, Hong Kong, China; (c) FPM 41 Building, Lisbon, Portugal; (d) Gravity loads path through the hanger transfer structure in FPM 41 Building [7]

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 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 (Figures 7a and 7b). 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 to 4 [8]. It has a shear

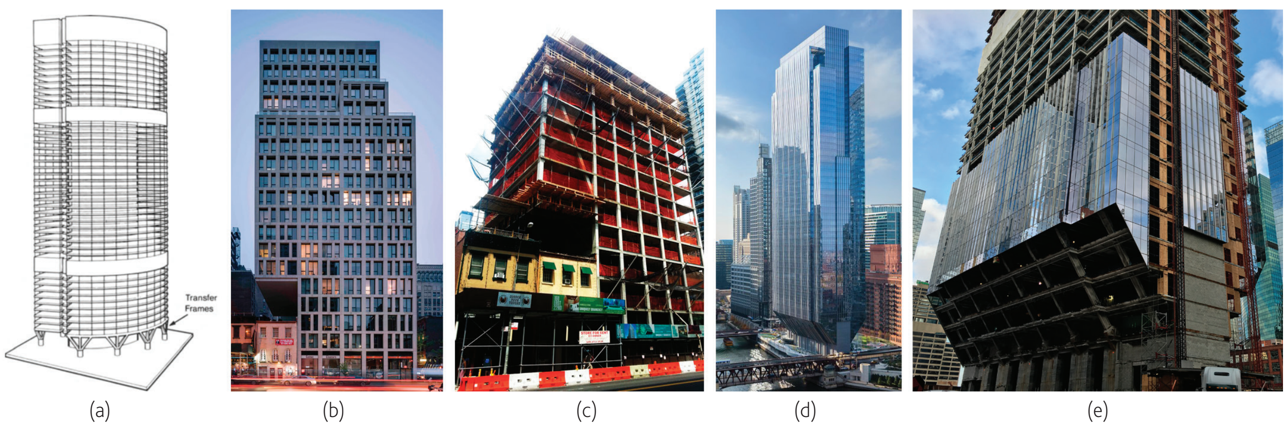


Figure 6 (a) Structural system of the Grosvenor Place, Sydney, Australia; (b) 160 East 22nd Street Building, Manhattan, New York, USA; (c) Inclined column view during construction of the 160 East 22nd Street Building; (d) 150 North Riverside Plaza, Chicago, USA; (e) Inclined columns of the 150 North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

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

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

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.

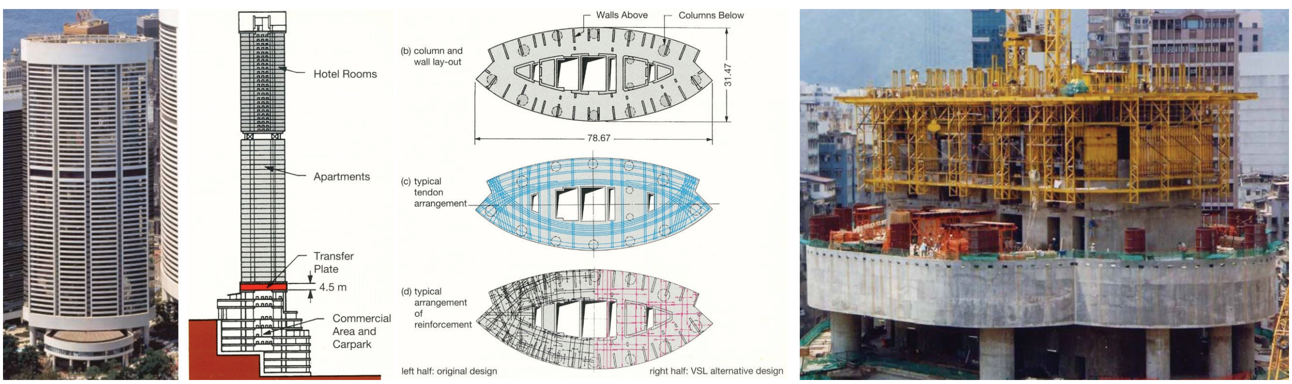
2.4 Plate

A transfer plate is a thick 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 m to 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.

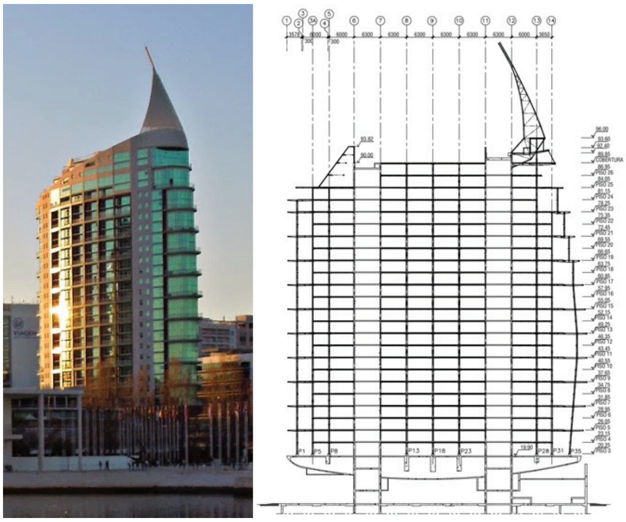
As the transfer plate usually extends the entire building footprint and has a thickness of up to several meters, it is a massive concrete structure with a substantial self-weight and large amounts of reinforcement, as illustrated in Figure 8. Post-tensioning of the transfer plate is an effective way of reducing the reinforcement quantities and the plate thickness and improving the cracking and deflection behavior [9]. 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 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 [10]. 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



(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 implications for the design of the falsework system. The beams are usually prestressed to reduce depth and reinforcement quantities.



(a) (b)

Figure 9 (a) Saint Gabriel Tower in Lisbon, Portugal, and (b) Saint Gabriel Tower structural system

2.5 Arch & Cable

The arch and cable 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. Figures 10a and 10b present two examples where the arch transfer system was employed, representing a defining feature of the buildings. Likewise, Figure 10c shows a building where the cable element was applied as a transfer structure, which may be referred to as a suspension system.

Reactive forces will develop at the arch or cable ends, which have both vertical and horizontal components [11]. 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 cable or a tie-rod in the case of the arch. Designing 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 structural design and construction of transfer structures

The design for deflection control is frequently the primary consideration when defining the dimensions of a transfer element, as transfer structures are usually prone to large deflections due to long spans and the high magnitude of the forces involved [12]. 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 [13].

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. Regarding the seismic design of the transfer structure, 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 [14]. 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.

The sequence of construction greatly affects the total deflections and the final forces distributions and should be properly accounted for in the design stages through a construction-staged analysis.

(a) (b) (c)

Figure 10 (a) Broadgate Exchange House, London, UK; (b) Ludwig Erhard Haus, Berlin, Germany; (c) Marquette Plaza, Minneapolis, Minnesota, USA

Considerations of robustness and disproportionate collapse may also be key for the design of transfer structures as these are often regarded as critical elements for the overall stability of the building [15]. Finally, connections design might be challenging in transfer structures due to very high forces and complex geometry involved, and the general seismic design principle of capacity based design should be followed.

Transfer structures usually create logistical construction challenges related to sequencing and erection of heavy elements, as well as formwork complications. Therefore, temporary support systems play an important role in the construction process and may have a considerable influence on the overall benefit of a solution. Transfer structures should always utilize the highest strength of materials that are locally available in order for these elements to be the most effective and constructible - this includes using high-strength concrete (HSC), high-strength steel rebar (HSR), and high-strength structural steelwork (HSS).

Regarding the construction of concrete transfer structures, the casting of large concrete elements, usually termed mass concrete, might be challenging as their thermal behavior is considerably different from ordinary concrete works, and high-temperature differentials between the core and the surface may originate early-age cracking. On the other hand, steel transfer structures usually require a high degree of dimensional control during fabrication and erection and the definition of a complex system of tolerances.

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 [16], 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 11. 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 & CABLE types.

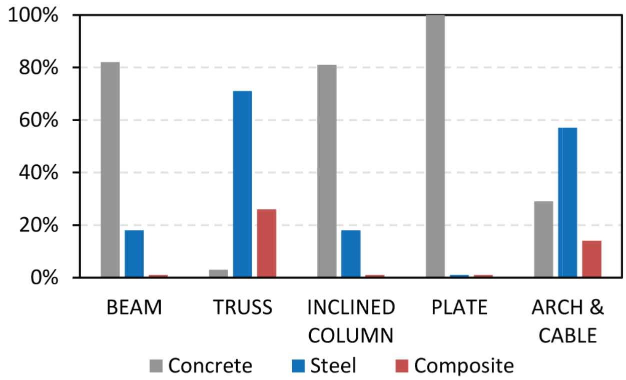


Figure 11 Materials employed in each type of TS

This is related with 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 & CABLE 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 12. 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 '70s 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 & CABLE 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 & CABLE schemes are particularly suitable to achieve long span transfers. Furthermore, the overall most common type of transfer structure is the TRUSS

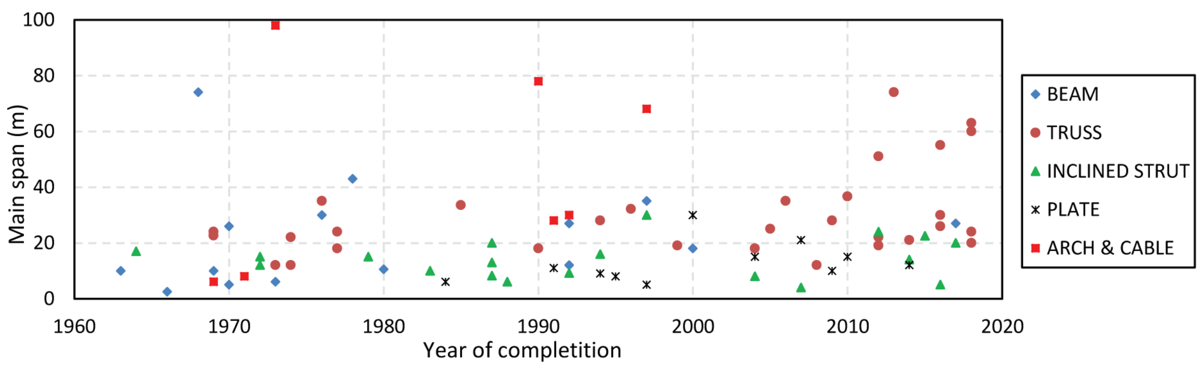


Figure 12 Year of conclusion and main span for buildings with global transfer structures (note: for cantilevered TSs, the adopted span was twice the cantilever length for a better comparison with normal span TSs)

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.

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