Chapter

Transit-Oriented Development Interactions on Existing Metro Systems: The Need for the Design of Adequate Structural Monitoring System and the Experience from International Projects

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Abstract

Contemporary metro transport systems present unrivaled efficiency for the commuting population. The development of the urban environment is interwoven with the metro transit systems. The transit-oriented development (TOD) is an upcoming topic in the design of the contemporary and of the future city and metro system alike. It entails the development of a microcell of the city centered around the metro station. Typically, bulky TOD buildings rise over and around the station and tunnel. The structural engineering aspect of these mega projects is highly complex. Major part of the complexity is due to complicated interactions between the oversite building and the underlying tunnel or station with its track-rail system. A significant number of issues arise, like methods to bridge over the tunnel or station, structural isolation, induced displacements to the track-rail system, tunnel movements and impact to tracks, vibration induction to the TOD building, and a plenitude of similar problems. It is highly important to design a structural monitoring system that will provide a validation tool of the structural-dynamic performance of the closed system TOD-tunnel/station. The distilled experience from international projects is presented.

Keywords: metro systems, tunnel stations, transit-oriented development, rail, track systems, displacement field, vibration field, structural monitoring, BIM

1. Introduction

This chapter is dedicated to a special engineering topic having to do with the structural interfaces of the metro to urban environment mega structures. The transit-oriented developments (TOD) are typically large real estate developments over or in the close vicinity of the metro stations. In the following, by the term metro is meant the whole metro installation including the tunnels, Stations and Switchboxes and all other structures like pop-ups and entrances. The social and financial importance of the TODs is very significant as they provide to the owner (usually the metro owner) great marketing privileges. The same time they are regarded as a major step toward the sustainable urban environment minimizing the use of cars (see for example [1, 2], also www.tod.org). High rise buildings for office complexes, residential or hotel apartments, schools and hospitals, large malls and all other elements of the contemporary city life are built over or in walking distance to the metro. Thus, the technical concept of the TOD is threaded together with major structural issues. On one hand, the metro must bear TOD rising above and sustain the construction and service life loads and displacements envelopes safely. On the other hand the TOD shall be designed and constructed so that the inevitable effects on the existing metro shall be minimum and in all times within acceptable limits, without reducing the Design Service Life of it. The same time, the metro activities must not be blocked during the construction of the TOD or any case during the service life of it, while the noise and vibrations need to be filtered out on their way up to the residential areas of the TOD. In order to succeed in all the mentioned difficult tasks, special structural engineering considerations must be made and construction methods must be employed. The significant degree of uncertainty regarding the existing infrastructure is combined with the sensitivity of the metro and track rail system as well as the ambitious superstructure of the TOD giving a very cumbersome engineering undertaking. This makes unavoidable to employ methods to monitor the structural performance of both, the metro and the TOD. The monitoring system, as will be discussed in the following pages must be considered to have high specifications reflecting the important aspects of the analysis and design. It should never be considered to be a construction task left to the discretion of the contractor alone. It should be rather designed tailor made for the aforementioned engineering challenges and construction methods.

A typical TOD-metro combination is depicted in **Figures 1** and **2**. The figures come from a purpose made BIM exercise. In **Figure 1**, there is a bird's-eye view, while in **Figure 2** there is a bottom view, to show the distinct parts of the combined foundation of the TOD and the metro.

In the next pages some important structural considerations shall be presented, as they come from the experience of the TOD design over the metro of Qatar (**Figures 3** and **4**).

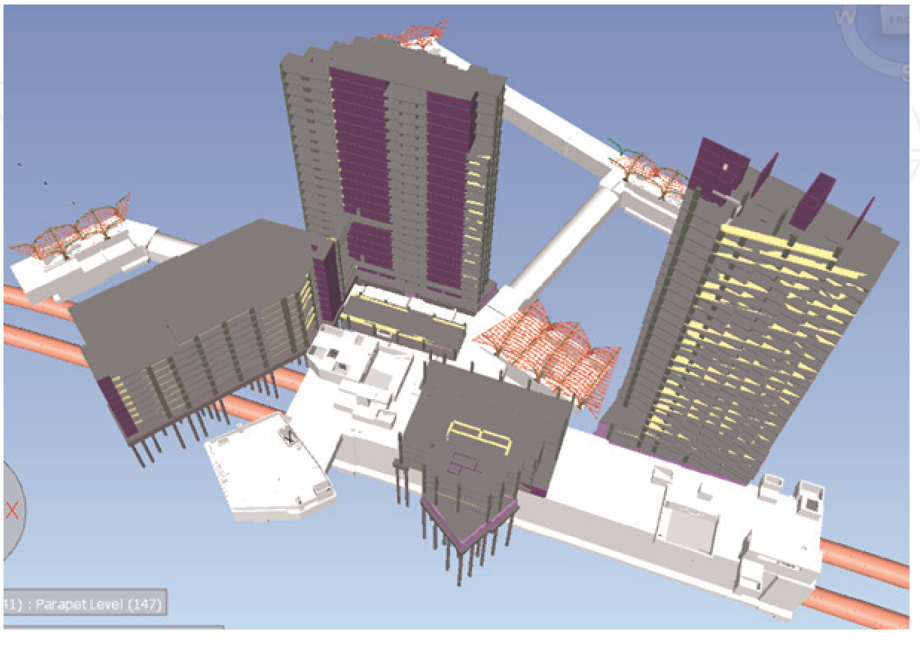

Figure 1.
Typical BIM overview of the structural compound of TOD (in gray) and the metro station (in white) and tunnel (red).

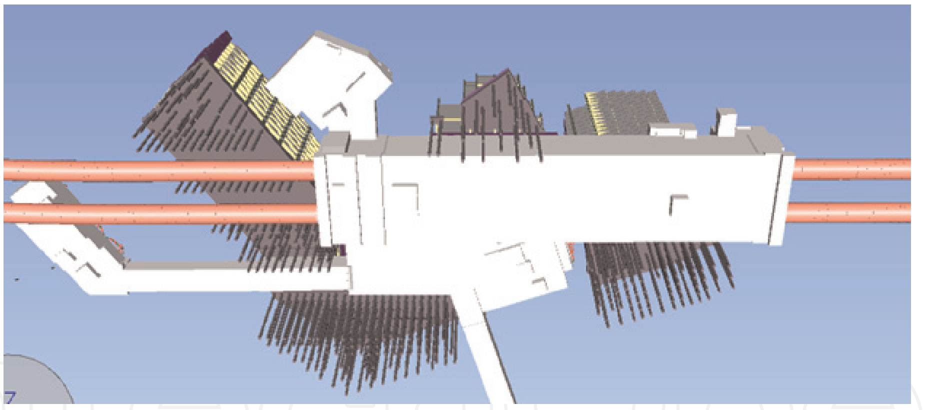

Figure 2.
The same BIM model seen from a bottom angle to reveal the TOD piled foundation around the metro tunnels and structures.

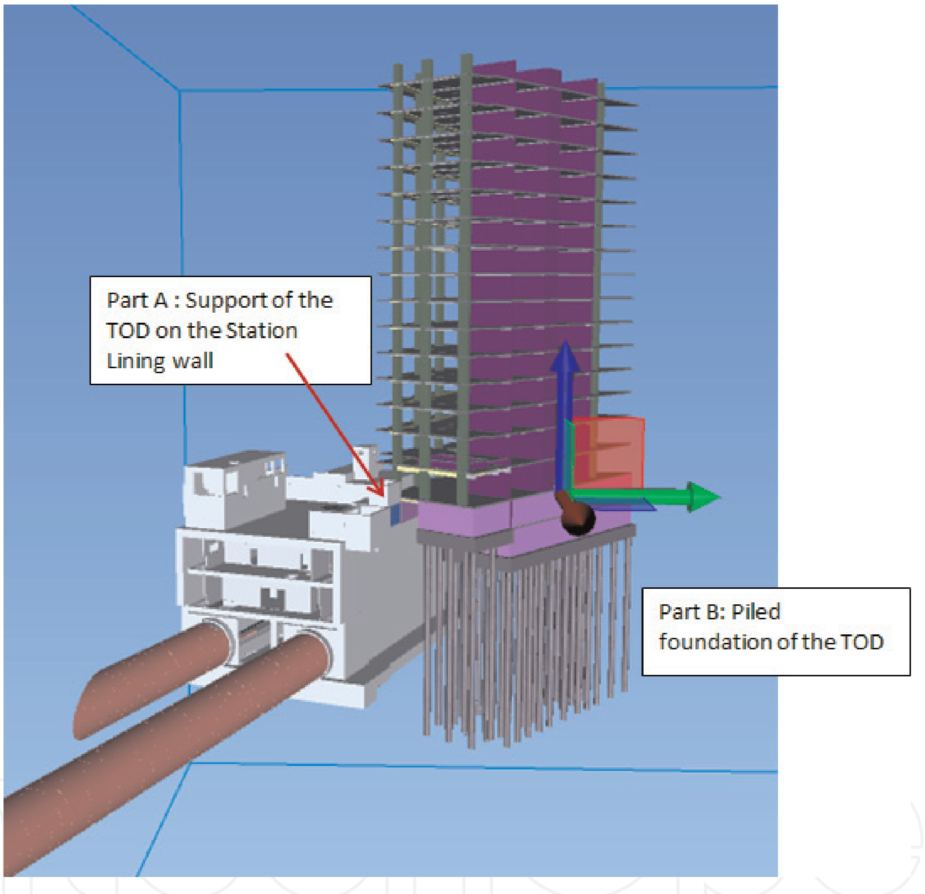

Figure 3.
Note the compound foundation system of the TOD. Part A is sitting on the metro, while part B is resting on a pile group.

More specifically, the following issues shall be discussed:

a. Structural assessment of the existing metro structures (codes to consider, total structural behavior of the underground and superstructure and sub-structuring),

b. Transfer systems (effects of transfer systems on the existing structures, configuration of pinned connection for the super structure),

c. Control of the noise and vibration induced into the TODs.

d. Displacement envelope induced in the existing track-rail system, either into the tunnel or at the Station-tunnel interfaces.

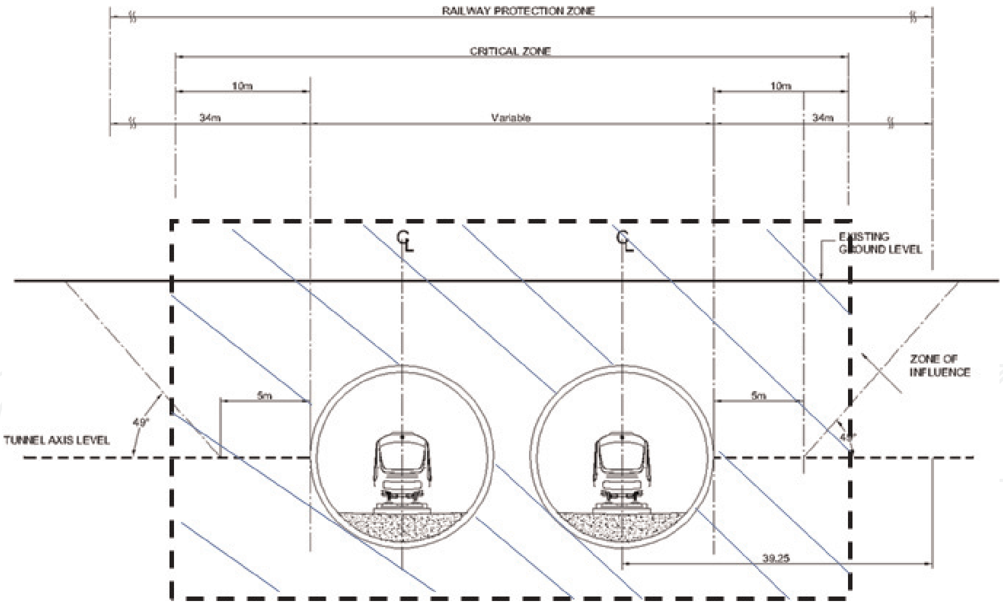

Figure 4.
Typical example of railway protection zone and critical zone around the metro tunnel.

e. Methods to insulate the metro from induced displacements.

f. Structural monitoring and control of the construction and final TOD during its service life.

g. Verification, validation and uncertainty quantification.

The challenges that are highlighted in this chapter lead to new unexplored areas which, as will be discussed below are:

i. Simulation and computing demands

This includes issues regarding potential Static condensation capabilities in Finite Element structural software packages and numerical treatments like rigid link considerations

ii. Multi-sensing monitoring—data fusion—situational awareness of Structural complexity

Special attention is given to the rail itself.

iii. Corrosion monitoring—corrosion mitigation. Incorporation into the multi sensing monitoring

iv. Special structural considerations like failure mode and effects analysis—fault tree analysis for critical structural members. There is a significant aspect of verification, validation and uncertainty quantification.

2. The framework of regulations for real estate development in the vicinity of the metro

The starting point for the design of any structural intervention in the vicinity of the metro installations is the set of rail authorities regulations as depicted in technical guidelines and standards.

It is very important to make a reference of such regulations in this starting paragraph, as these constitute a prerequisite to any construction or structural activity near the metro and provide a glimpse of the structural issues of the metro-TOD interaction.

In most countries with advanced rail assets there are regulations regarding the permitting for real estate developments and in general construction activities by any third party in the vicinity of the rail-track.

Typically, there is a definition of the rail corridor which follows in a notional path on the ground surface the route of the rail track either, tunnel, at-grade or elevated.

Into the rail corridor, in general, there are conditions and requirements to be fulfilled in order to permit the construction activities. There is however a narrow zone, the critical zone, around the tunnel (in the case of underground metro) where the construction is in general prohibited. It may be allowed only after meticulous calculation of the effects on the metro assets, the tunnel and the rail-track system. In this case it seems that the most suitable analysis of effects may come from a Finite Element soil structure interaction analysis which should be very accurate in the calculation of the displacements of the rail.

In **Table 1**, a typical grading of the restrictions onto the railway corridor is depicted, depending to the proximity to the rail assets.

In general, into the Protection Zone there is a requirement for application for permit. During the review of the development all aspects of safety and operation of the railway are considered. There may be restricted construction activity, but the development is in general possible. The restrictions reflect the three major clusters of risks for the railway. The first is the risks related to potential damage to the structural part of the railway infrastructure like the tunnel concrete lining, the station, emergency exits, pop-ups of all kinds, etc. The second is the potential effects or blocking of metro operations due to construction activities close to entrances or pop-ups. A typical example is the risk of flooding to the existing metro installations due to excavations, earth moving and other construction site operations. But the most sensitive family of risks lays in the effects of the construction on the rail displacements. The tolerance to the rail displacements is always very small. The reader is referred to [3–7] for detailed presentation of the capacity of the track system to absorb displacements induced by the various construction phases. Especially the Deutsche Bahn standards are very sensitive to the lateral displacements at all expansion joints. For example, the expansion joints between the station to the switchbox, or even worse the tunnel to the station are very critical areas to check the induced displacements due to the construction program of the TOD.

It is the experience of the rail and metro authorities, that a soil structure interaction analysis will reveal the effects on concrete structure of the metro and the induced displacements on the rail. Moreover, some special construction restrictions

Zone	Permit	Restriction Level
Protection Zone (as depicted on surface)	Possible	Restricted
Influence Zone	Exception	High restriction (with limitations) – Special structural requirements
Critical Zone	Exception	Very high restriction (with limitations) – Special structural requirements

Table 1.
Grading of the construction activities depending on the proximity to the rail asset.

or requirements should be imposed. For example the piling into the influence zone and especially into the critical zone may be required to include sleeves in order to reduce the development of pile skin friction. The pile sleeves are usually required down to approximately the depth of the tunnel invert, or to a depth under which there is no practical effect on the tunnel or the rail.

Monitoring of the tunnel or station and especially of the rail is a very important requirement in this case. The necessary accuracy and precision is important to be validated, but equally important is the real time character of the monitoring and reaction time for application of mitigation measures. A more detailed analysis of monitoring requirements shall be made in Section 3.9 of this chapter. For the purposes of the current paragraph it suffices to emphasize the real time character of the monitoring coupled with readiness of suitable mitigation measures.

Therefore, for any real estate development project within the rail corridor, the rail authority sets the following considerations regarding the existing metro structural assets:

Critical structures and issues:

a. Station concrete shell

b. Metro operation and construction restrictions

c. Tunnel concrete lining

d. Existing state of damage—cracked state of existing metro infrastructure and level of water ingress

e. Existing reinforcement corrosion state—potential stray current

f. Existing structure sensitive areas condition: sensitive items like the expansion joints, slender structural members or members with high utilization factor like columns, struts, pier heads working under very heavy punching loads.

g. Induced displacements to the rail. Special focus on the interface between tunnel to station, expansion joints between station parts or station to switchbox, bridge to station, etc.

These considerations should be a prerequisite to any transit-oriented development structural design. Moreover, the structural monitoring requirements focused on the rail behavior, usually becomes the central part of the broader monitoring program of the TOD. The structural assessment of the existing Rail infrastructure becomes the starting point of the design phase. A more detailed presentation of the structural assessment of the existing structures shall be made in Section 3.2.

3. Transit-oriented developments over existing metro installations

3.1 Building extension over the metro station: the modeling issue

In this section it is asserted that indispensable part of the structural analysis and design of the transit-oriented development (TOD) structures is the study of the effects on the existing metro structures (metro). Moreover, as the structural response of the TOD depends heavily on the underlying metro, the numerical simulation must include both of them. It should be highlighted that structural interaction between the two structures TOD and metro exists even if the direct mechanical connection is partial.

Experience from TOD projects shows that it is a widespread belief among the various stakeholders that whenever there has been provision of a future Oversite building loading during the initial design of the metro, design work for the TOD could be eased and limited only to the superstructure part alone, i.e., the TOD itself. A widespread belief is that probably, the only care for the metro should be not to exceed the "allowable TOD reactions" for which it was initially designed. However, this is very rarely enough, as the existing metro forms part of the total structure. In other words the TOD and the metro are a combined structure. In this case, the stakeholders need to understand and consider the cost and risks that stem from the combined metro-TOD structure. More specifically, significant effort is needed to incorporate into the design of the TOD the metro as part of the total structure.

A dominant parameter for the design of the existing metro stations and tunnels is undeniably the future prospect of a major oversite building. This is reasonable and expected as a high rise superstructure connected to the underground metro installations, induces significant reactions and displacements. This is primarily due to gravity loads, but lateral loads (due to wind and earthquake) exerted on the building may also produce dominant loading combinations. Critical construction stages which may include one side excavations, leading to unbalanced lateral earth pressures, also turn out to be very demanding tests for the metro. Depending on the construction program the loading on the metro may be highly non-uniform, leading to structural loads for which it is not designed. At the time of the design of the existing metro structures, the actual architectural configuration of a future oversite building or buildings may have not been entirely known. Far less would be known the construction stages necessary for the actual TOD. Therefore, gross assumptions may have been taken into the structural design regarding the prospect transit-oriented developments. These assumptions comprise an initial necessary condition for the structural design as far the bearing capacity of the metro is concerned. The satisfaction of the necessary and sufficient condition for the metro to undertake the effects of the TOD is checked by the simulation of the precise configuration of the complete connected structure of the underground metro installations and the TOD superstructure, following the real construction phases. Both the existing metro and the TOD along with their structural connections and TOD independent foundation elements should be simulated as accurately as possible.

The ideal method to perform this simulation would be to incorporate in one model the whole metro and the TOD superstructure. The continuous modeling of the total structure, underground part and superstructure, in one model provides an uninterrupted displacement and stress flow. Arguably, this leads to safer results than any set of separate analysis of the metro, the TOD and their subassemblies. The benefits of the unified approach are pronounced in analysis for lateral loads from wind and earthquake. The computational cost, however, becomes an unsurpassed obstacle for this. The trivial method is to subdivide to two substructures, the underground metro box and the superstructure TOD and perform separate analyses. In this case the risk lurking is the intermediate and tedious phase of manual insertion of reactions from one substructure to the other. Apart from being a very tedious procedure which leaves large room for error, the risk of inadequate simulation of the total-unified response is always there. The soil-structure interaction in this case proves to be far more complicated, especially when the construction phases of the station box and the TOD building are distant to one another. A comprehensive study of this subject has been elaborated by O'Riorden in [8].

A substructuring method, if available, using static condensation to form super-elements for the underground part and the superstructure would provide better control of the modeling work and better approximation of the structural response of the total structure.

3.2 Structural assessment of the existing metro assets

It is highly recommended to perform an initial analysis of the metro as it is, prior to the introduction of TOD or its construction phases. This should be part of an initial structural assessment of the existing structure. This initial analysis may help to understand the structural response of the initial structure and reveal sensitive areas and critical failure modes.

Significant parameters to consider at this phase of the design have to do with the standards with which it was designed, the foreseen and the actual loading conditions but also with the current structural condition of the metro. Especially the crack formations and potential water ingress through cracks, voids, and construction joints, need to be taken seriously into account. The corrosion level of the reinforcement should be considered in case there are signs of corrosion or even better if there are measurements for the corrosion potential. It must be born in mind in this case that an allowance for the structural capacity should be made to simulate the cracking and the reinforcement section loss. The designer should carefully consider the actual stiffness of the metro. Potentially, a reduction of the modulus of elasticity should be considered.

In the structural monitoring section of this chapter, it will be mentioned that corrosion monitoring and mitigation should be introduced and should become part of the holistic structural health monitoring schedule of the total structure (metro and TOD).

In order to confront such structural assessment and modeling issues, appropriate sets of standards should be employed (see for example [9–12]). The standards for the assessment should deal with the necessary investigative works for the potential concrete deterioration, precondition surveys, etc. as well as the bridging of the design standards used for the existing structures and the current ones with which the TODs are under design. It is very important also that the design code employed will provide guidance on special modeling aspects pertinent to the special structural system of the combined TOD and Station box. American set of standards like ASCE-41 [9] and FEMA 356 [10] are more adept to provide guidance for existing structures of such importance. They also provide significant guidance for the numerical modeling. In the Euronorm family of standards, one can seek limited guidance in EN1998-05 (although this standard is dedicated to earthquake engineering) and the Greek Code of Structural Interventions [11]. Qatar Rail has compiled a necessary set of investigation practices as well as structural assessment best practices in Ref. [12].

Realistic reanalysis of the structure must not be over conservative. If it's conservative it'll prove the tunnel or the station inadequate to withstand the loads or the induced displacements. Careful selection of assumptions must be made in order to depict the real structural condition. Typical example is the simulation of the massive concrete joints of the existing structures. For example the "knee" and "tee" joints of the station box and also the joints of the columns to the massive bottom and top slabs require careful design of a rigid link.

3.3 The transfer systems

The challenge of having a transfer system spanning over typical metro stations has been detailed in many significant publications, with some key references can be found in [13, 14]. The typical transfer slab is characterized by massive concrete and usually by a small span in comparison to its longitudinal direction. In what follows, structural members made of massive concrete (MC) shall mean members with thickness more than 1.5 m and which are prone to exhibit high temperature gradient across the thickness during concrete hardening.

Figures 5 and **6** depict characteristic configurations of transfer slabs spanning over stations.

In the case of direct connection of the TODs to the station box a secure path of stress flow from the superstructure to the station box is needed. The station box acts to a great extend as a foundation to the TODs, as a multi-cell concrete box circulating the stress flow between the lining walls and the main slabs (base slab, concourse and roof slab). However, there are sensitive structural members of the interior of the station box, like internal columns and stress concentration points due to openings that set limitations to excessive deformation due to the effects of the TOD superstructure. The most efficient way to transfer the TOD's actions on the station

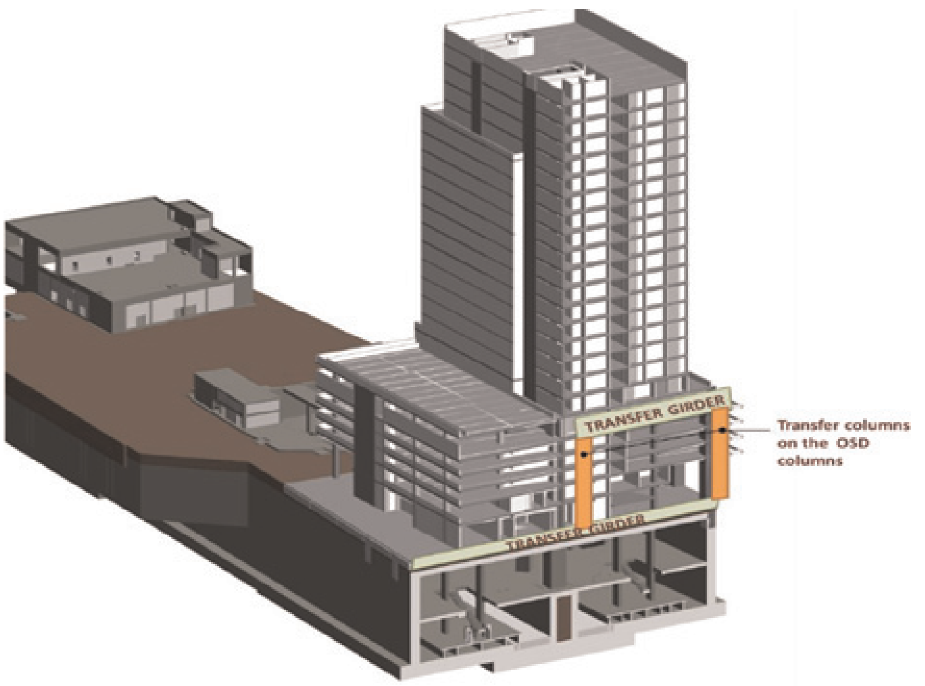

Figure 5.
Typical configuration of a transfer slab over a metro station. Note the oversite development (OSD) building transfer columns and their load redistribution role.

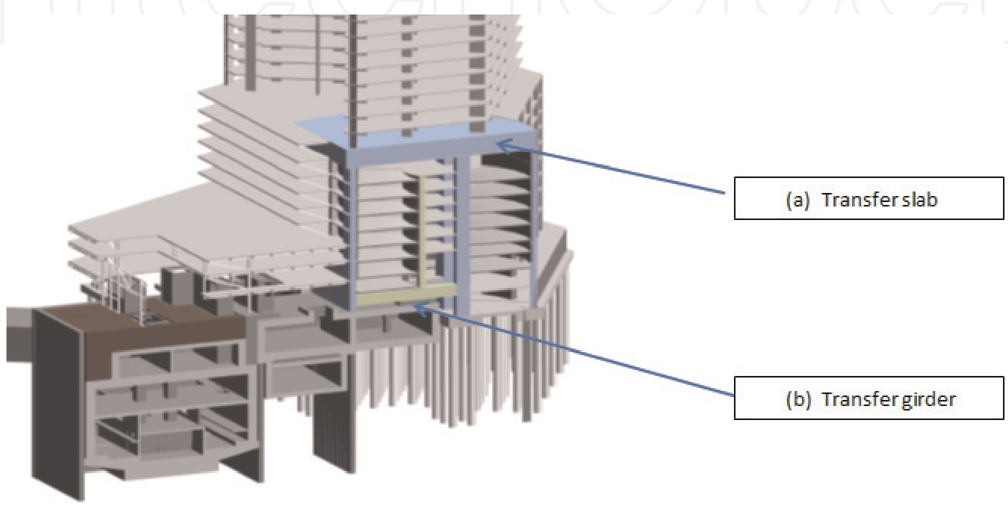

Figure 6.
Transfer slab (a) at elevated position and (b) transfer girder.

box's hard points is the utilization of a transfer system that passes the reactions of the TOD's columns and cores at selected anchor points of the lining walls of the station (see for example **Figures 7** and **8**).

This transposition of vertical forces can be done either in the form of a massive concrete slab resting right on top of the lining walls and spanning over the roof slab of the station, or at any level above and well into the structure of the TOD (see for example [14]). Massive concrete considerations must be performed, including thermal stress, early age and long term cracking, etc. Heavy post tensioning sequence steps must be considered given the span of the slab over the station. The massive character of the slab helps to absorb vibrations from the station before they enter into the superstructure of the TODs, performing thus as the first line of defense for vibration isolation. In the case of the transfer system at elevated position, a hanging system is formed, usually employing deep steel trusses.

From the structural system point of view, the method of the massive concrete transfer slab resting in close proximity to the station box seems to have great benefits. The center of gravity is close to the station-foundation and provides small lever arm to the top of the "knee" joints of the station box. The connection to the lining walls can be made to behave as a pin with little effort. A potential draw back of the position close to the soil surface is the exposure class for the durability design, which in this case is harsher.

On the other hand the pop-ups of the station box and other surface utilities may obstruct the position of the transfer slab at that level. The architectural and mechanical engineering requirements are many times such that the position of the transfer system at an elevated position is one way to go. The lever arm of the mass

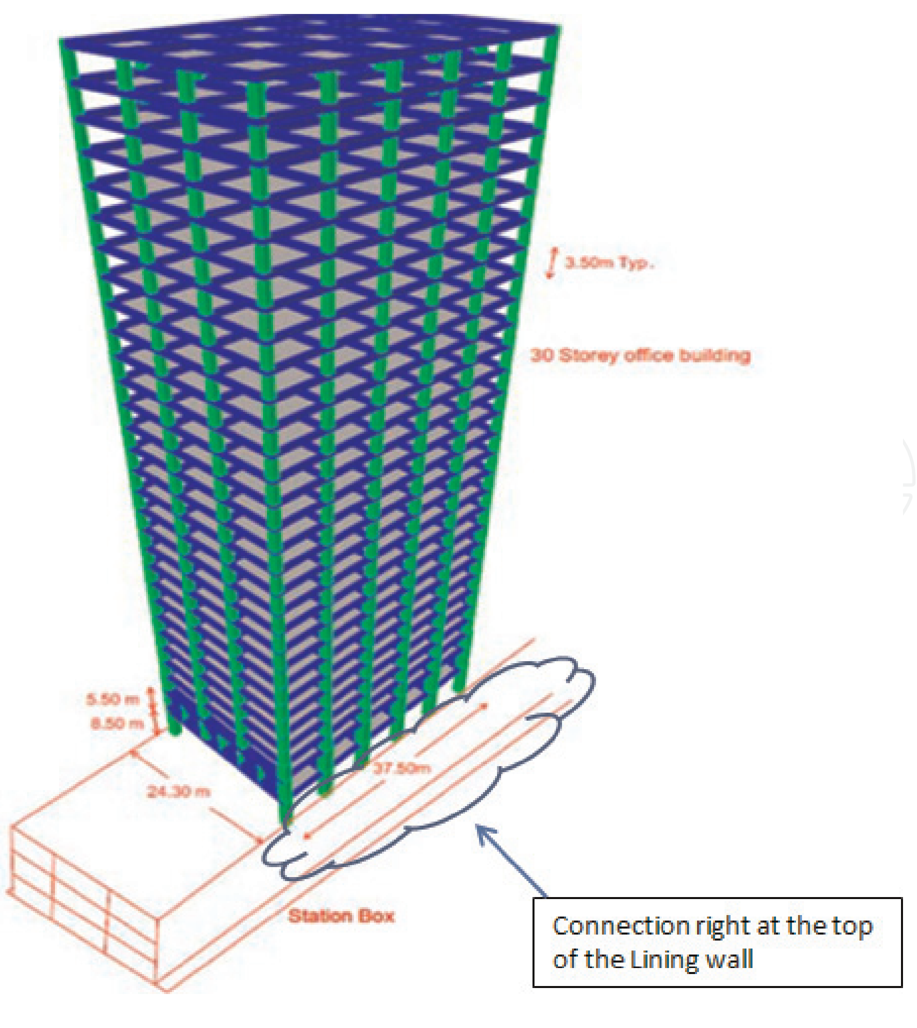

Figure 7.
Idealized "module" of TOD "loading" all along the lining walls of the station box.

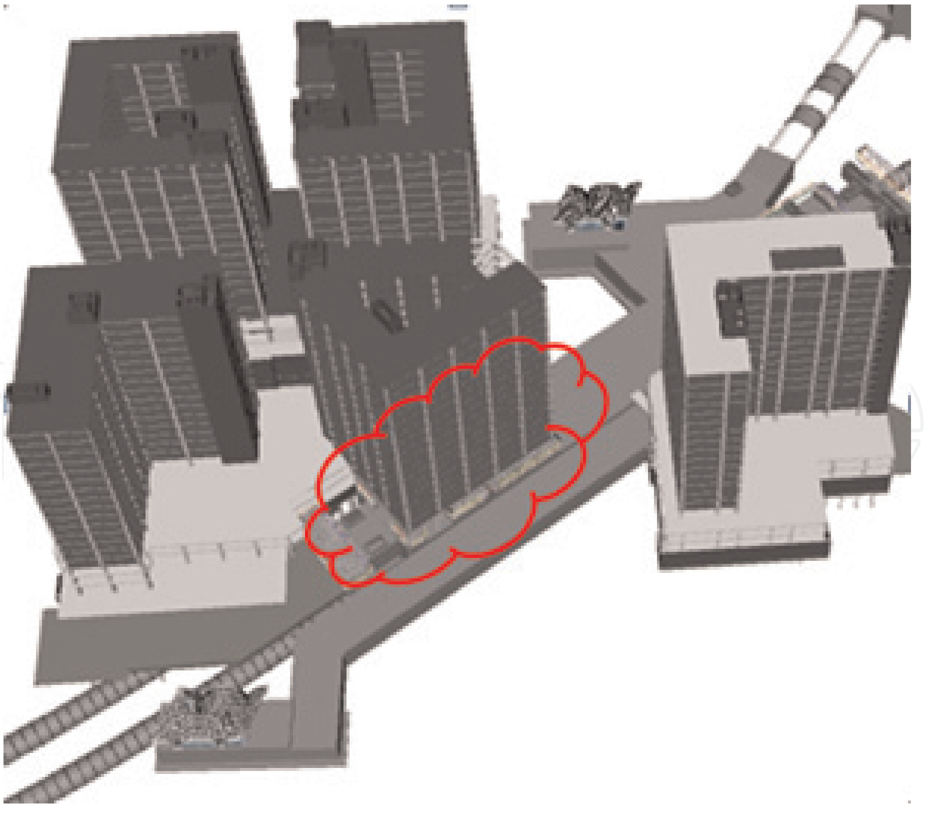

Figure 8.
*Actual TOD building configuration on top and besides the station box—in contrast to **Figure 1** of the initial concept. The reader should notice in the cloud the half-treading of the building only on some part of the station.*

of the transfer slab is then very great, producing significant bending moments during lateral loadings. The construction of the slab at an elevated position is by itself a significant construction task, involving difficult logistics and heavy false-work the design of which is a cumbersome undertaking (**Figure 9**).

3.4 D and B regions in concrete beam analysis

Flexural behavior of beams and therefore slabs is well coded in international standards providing specific conditions apply which signify a more-or-less known stress flow pattern. This behavior is generally known as Bernoulli or Beam type (B type) flexural behavior as it complies with Bernoulli conditions of flexural behavior. In contrast, areas of beams or slabs that do not fulfill the necessary conditions for a Bernoulli type flexural behavior present a more complex, unpredicted and spurious stress flow, which necessitates delicate computational mechanics analysis methods. They are usually designated as D regions, named after the disturbed or discontinuity regions (see **Figure 10**). The only closed-form analytical method alternative to expensive Finite Element methods accredited by international codes is the strut and tie method. The success of the strut and tie method relies upon the experience and "art" of the modeler. Usually, it is employed for validation purposes rather than for the main design procedure. Certainly, the criticality of the transfer slab and the risks/impact involved requires a fool proof method, capable for representation of the full stress field in every region. These requirements are very high, well above the capacity of the ordinary Finite Shell element method or the strut and tie method.

The transfer beams and slabs differ from the ordinary, so as to say, everyday beams and slabs due to the ratio of their thickness to their length. There is no doubt that these slabs contain areas that belong to the D regions. Their thickness to span

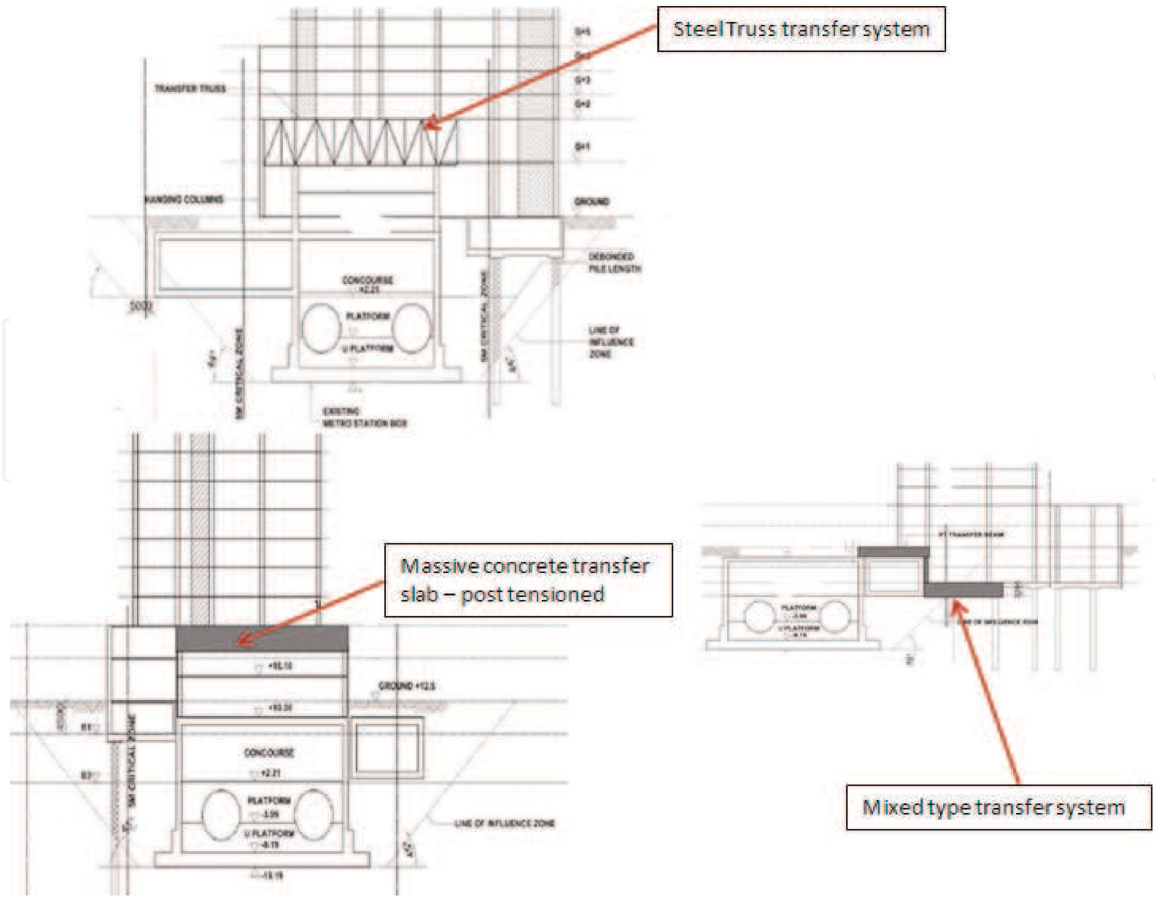

Figure 9.
Typical examples of the diverse methods of transferring the load through slabs-girders—trusses.

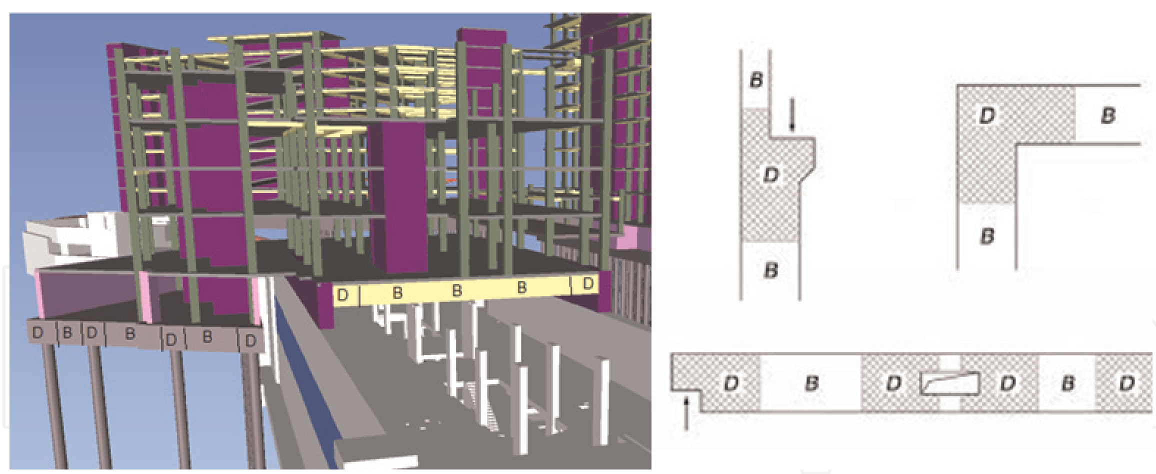

Figure 10.
Typical examples of D and B regions in transfer systems.

ratio and the MC joints produce stress flows that do not comply with Bernoulli beam bending theory. The classic Bernoulli beam bending theory may only be valid under certain conditions for it to be applied. Thick shell Finite Element methods can in some cases be a remedy, but the problem may persist in cases where the geometry does not allow discretization with shell or line elements anyway. The consideration of appropriate numerical treatment of D-regions, or in other words a non-shell-element FE area may be decisive for the correct analysis (**Figure 11**).

Moreover, all the mentioned D regions and concrete joints require dedicated methods of analysis, apt to simulate the Saint-Venant principle due to the

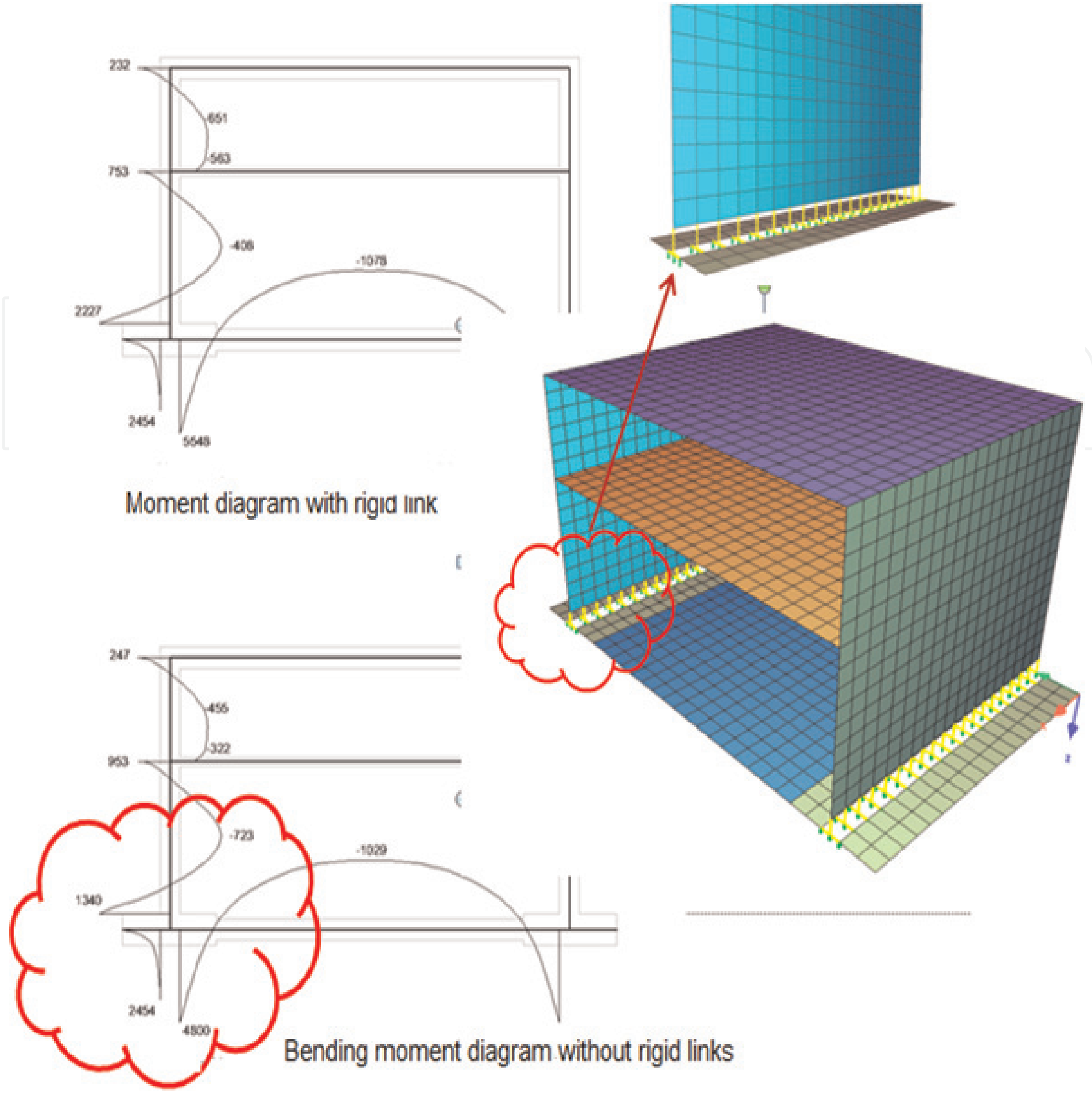

Figure 11.
Characteristic case where FE shell elements without treatment of critical areas is inappropriate. The bending moment at the connection of the wall to base slab is 66% higher when rigid link is used.

complicated stress bursting there. Posttensioning of the slab or girder contributing to strong stress bursting exacerbates the analysis complexity and increases the finite element requirements.

Methods capable to perform accurate simulation of the stress-strain flow of the transfer slab are either numerical simulations based on solid-3D elements or laboratory tests. The most accurate Finite Element methods to treat the MC and D region problems incorporate 3D and non-linear analyses. Thus, the work load and numerical effort needed increases significantly as well as the assumptions log.

The transfer slab analysis must take into consideration the massive concrete nature of the particular structural element, especially at its connections. The classic linear analysis, as this is offered by linear shell element analysis, may be inappropriate. The linear beam analysis assumptions, and especially the Bernoulli assumption of plain section rotations, usually are not applicable. The nature of this structural element is a thick shell. The infusion of stresses into the transfer slab is following a Saint-Venant bursting stress pattern that is not possible to be simulated with a mere rod-like line element approximation. Either an efficient local Finite Element analysis should be employed, or an appropriate strut and tie local model should be used to simulate the stress distribution in the joint.

To this point it is important to note that the concrete joint analysis of both the underground structure and the transfer system or other similar TOD massive structures must take into account rigid link analysis, wherever appropriate. As far as line-type elements, ASCE [9] and FEMA 356 [10] provide guidelines for the estimation of the length of the rigid link, with the ASCE standard being somewhat more sensitive to the actual concrete configuration. Birely et al. [15] offer a more delicate approach to this critical FE analysis issue (see also [16, 17]). Similar approaches should be followed for the MC joints formed by the surface members of the metro and TOD. The MC joints formed by the slabs and walls of the metro and the TOD transfer slabs and their connections are similar to the line element joints for which the mentioned literature is dedicated, although the actual engineering mechanics problem may be somewhat more complicated due to the influence of the stress components in the cross direction to the joint. It is to be noted that there aren't enough experimental or numerical analysis results published for this type of concrete connectivity.

In any case, neglecting the rigid link at the massive concrete connections may result in significant underestimation of the developed stresses and consequently the reinforcement requirements. Apart from the pure engineering mechanics fact that the core of the MC joint behaves differently from the field of the converging wall and slab, there is also a simulation necessity to incorporate a type of a rigid link. In **Figure 12**, it is evident that a refined FE discretization is not appropriate to simulate

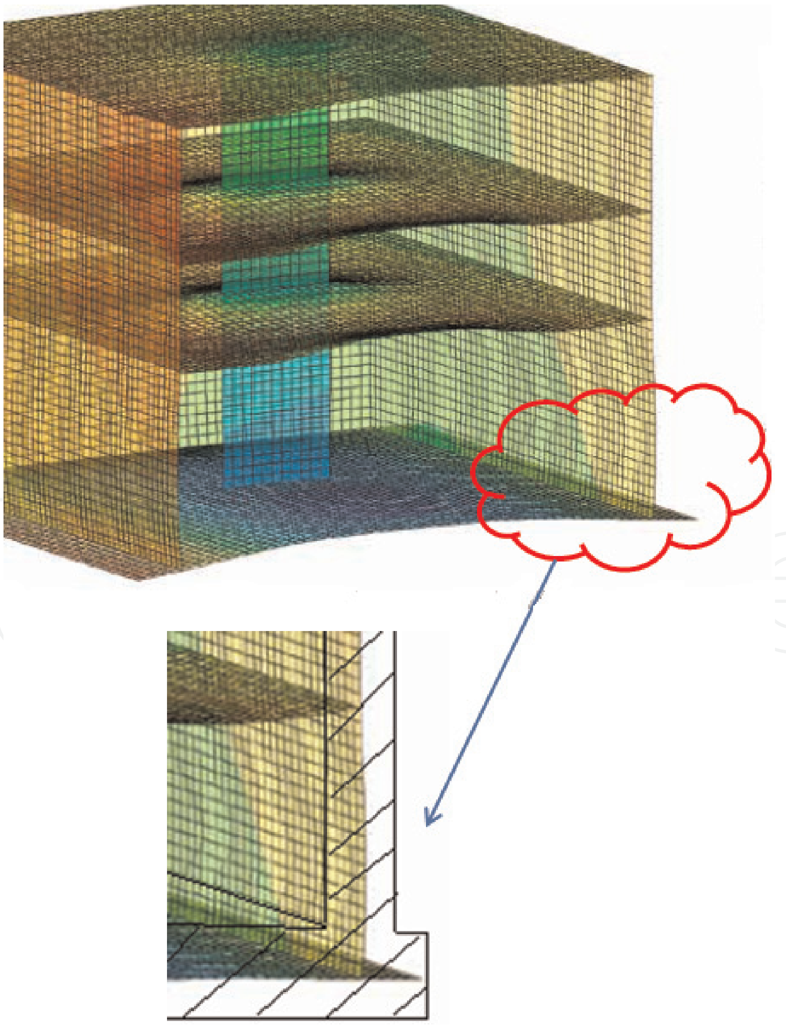

Figure 12.
A typical FE discretization of part of a station box. The actual concrete joint cannot be represented properly by the selected FE modeling. In the current configuration, which does not have any modeling treatment like a rigid link, the FE nodes that are located into the actual concrete joint do not represent the geometry or the stiffness of the joint. Obviously the shell-like representation chosen is inappropriate there.

the core of the joint with the same type of FE as with the fields of the slab or wall. A similar geometrical problem is evident at the connection of the columns to the MC slabs—with more important the thick base slabs. If no rigid link is introduced, then the size representation of the column may be largely different. Potentially, an envelope of a lower and upper bound stresses corresponding to analysis with and without rigid link may provide a conservative approach.

3.5 Connection of the transfer system to the metro structures

In the case of transfer system at an elevated position, the connection of it to the station box has a further complexity. Necessarily there will be vertical elements connecting it to the lining walls, but in this case significant bending moments will be induced into the "knee" joints of the roof slab (**Figure 13**).

This is unavoidable, because of the lever arm of the transfer slab and the slenderness of the vertical connection elements. The analysis of the existing "knee" joint must incorporate the joint stress flow appropriately. A pure and genuine pin and bracket connection is usually prohibitive, due to the magnitude of the gravity loads of the TOD. The requirements for water tightness and durability add greater difficulty in properly designing and constructing such configuration.

On the other hand an existing concrete station box may not have been designed for such additional bending moments, as, in the usual structural provision for future extensions, only vertical and horizontal components are considered. Therefore, the structural assessment of the existing structure must include the investigation of the "knee" joints of the existing metro structure.

A typical approach for reducing the bending moment development on top of such "knee" joints of the existing structures, involves a doweled connection configured primarily for shear (see **Figure 14**). It is noteworthy, that such a configuration may be simulated by a pure pinned connection for the TOD building with sufficient accuracy. This however, does not apply for the underground structure. Parasitic bending moments shall be developed, which may prove to be significant for the concrete shell of the existing structure.

In such a case, it is necessary to investigate the actual rotational spring acting at the interface of the new wall or column resting on the existing "knee" joint. Either the actual moment rotation diagram of the concrete cross section may be used, or even a potential works analysis of the structural element rising above new structure may be used, to provide the rotational spring at that support of the TODs. A

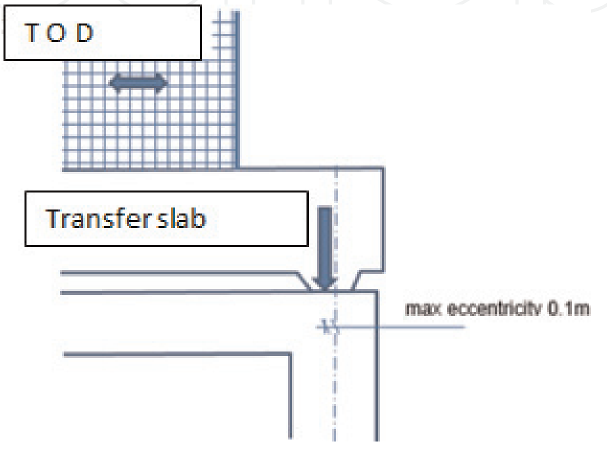

Figure 13.
Typical configuration of the transfer slab concept on top of the station roof. Note the close position of the rigid transfer slab to the top of the lining wall. In this case the concept of pinned connection may work sufficiently.

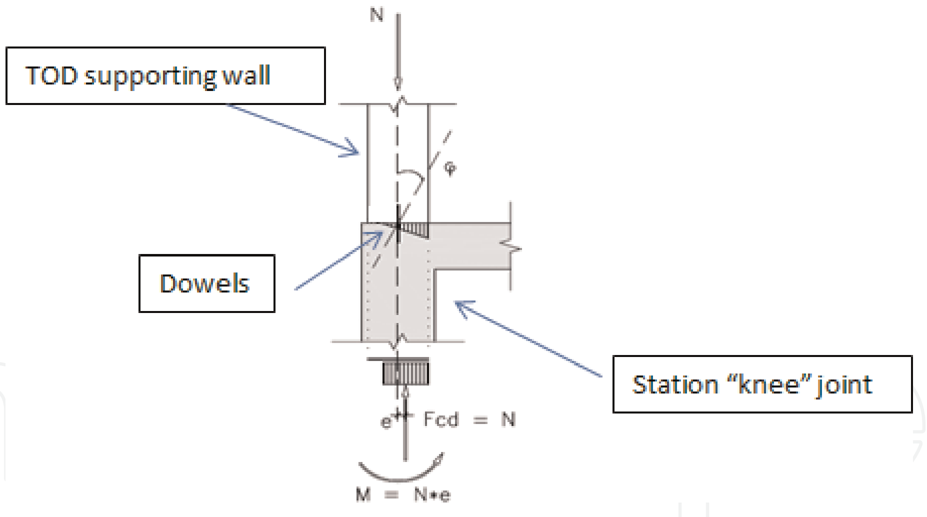

Figure 14.
Typical development of parasitic bending moments due to dowel articulated connection between TOD supporting wall and station "knee" joints over the lining wall.

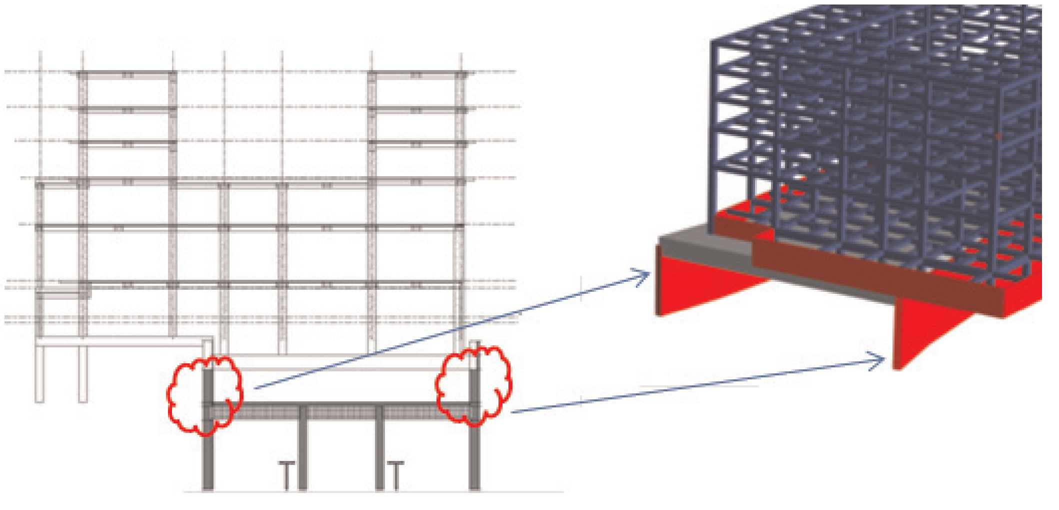

Figure 15.
Connection of the TOD to the station "knee joints" of the station roof. The connection is meant between retaining walls and lining walls.

subsequent building analysis shall provide the parasitic bending moment, which in most such cases proves to be not negligible at all (**Figure 15**).

The usage of the transfer system smooths out the concentration of vertical forces induced by cores and arbitrary distribution of vertical elements in general. If, however, there is partial occupation of the plan view of the station area, then there is necessarily a bending effect on the station box that the transfer slab cannot mitigate. This is further aggravated by the lateral loads (wind and earthquake, if applicable) that will induce a torsional deformation shape to the station box. Openings and entrance interfaces will develop significant stress concentrations that need to be checked. A critical point may be internal columns. These may already have a significant utilization factor, due to the complex behavior of the station stress flow. Given the bending and torsional deformational behavior of the station box, due to the TOD effects, buckling and punching at the pier heads shall be checked thoroughly (see also [17]).

3.6 Thermal dissemination due to massive concrete hardening

One major challenge of MC is the significant thermal loading developed during hardening and the corresponding thermal strain gradient throughout the cross section of the member. As the thickness of the MC is significant there are great temperature variations between the core and the outer skin of the member. It is noted that, this type of temperature loading is a highly non-linear and depends heavily on the thickness of the structure and the construction phases and joints provided. In the overall performance of the member, post tensioning analysis should take into consideration the residual stresses and strains due to hardening thermal loads. When highly aggressive environments must be considered, like for example in Qatar and in the Arab gulf states, in order to combine the necessary mechanical strength required and also to withstand the local weathering effects by corrosive agents and sulfate attack, a typical choice is to use high strength concrete mixes that provide solutions to many of the mentioned challenges. Concrete mixes with high percentage of binder like Grand Granulated Blast Furnace Slag (GGBFS) becomes often the choice. Nevertheless, there is still high risk for internal cracking of the MC, and this requires careful thermal dissipation analysis, shrinkage restraint analysis and construction joints design. Multiple layer construction and post tensioning increase the analysis and design demands.

The restrains to the slab or beam contraction may also be an additional analysis task. This is especially true in the case of MC transfer slabs acting as pile caps as shown in **Figure 16**. The pile head rows provide multiple restrain lines as they act as anchor points. The shrinkage and thermal loads may impose to the slab significant contraction strains and consequently the piles may experience very high shear loads. Crack development of the slab becomes the major design concern. FE analysis of the restraint of the slab due to shrinkage should rather be made on conservative assumptions. As far as the early age thermal cracking, CIRIA 660 Report [18] on early age thermal crack control offers some guidance on the type of restraint

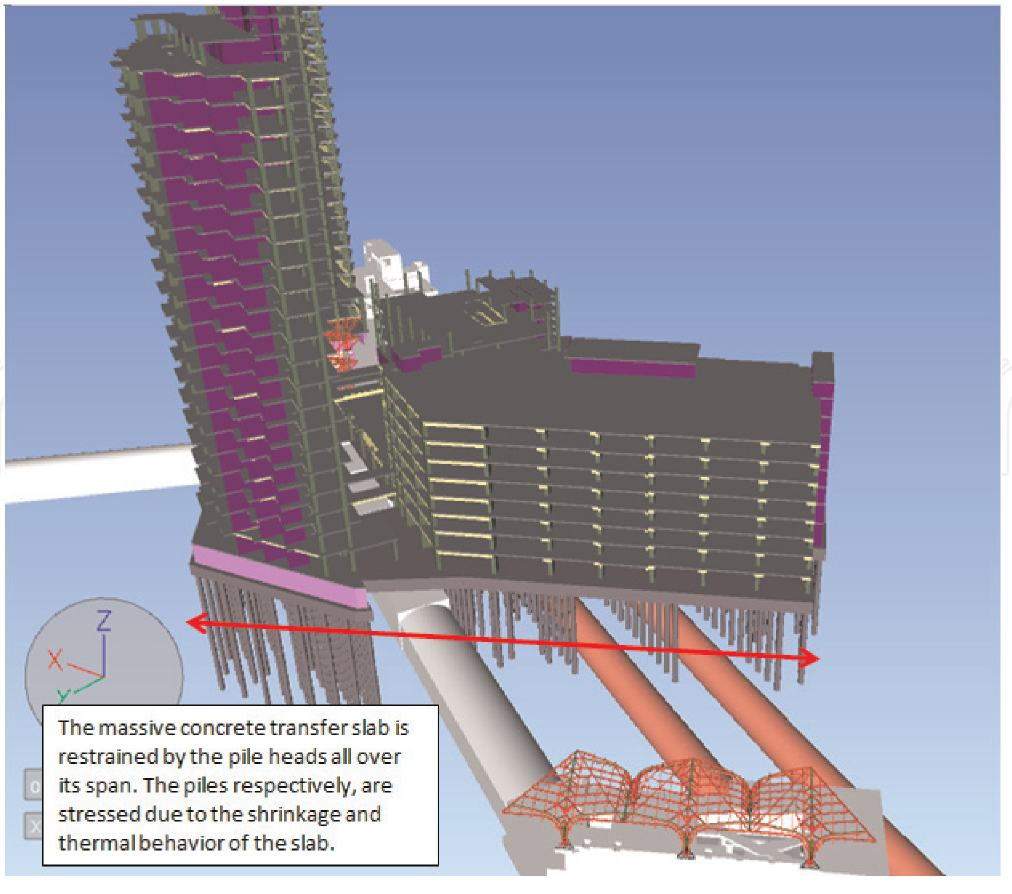

Figure 16.
Arrangement of the TOD over the tunnels and the pedestrian walkway. The transfer slab resting on the heavy piling in this case has a significant dimension. The massive concrete thermal considerations must be combined with the restraining effect of the piles.

formed. The analyst however, should be very cautious in his simulation of the boundary conditions whether there are conditions favoring end restraint to the notion of CIRIA 660. Stress concentrations due to abrupt stiffness changes, thickness, holes, may favor localized cracking rather than a somewhat evenly distributed crack pattern similar to the edge restraint pattern implied by CIRIA 660.

It is very important to perform mock ups of the transfer systems for calibrating the whole concreting procedure. Fruitful results also become available for the detailed design. Even so, structural monitoring of the performance of the actual transfer system is necessary. This is further discussed in the later section of this chapter regarding monitoring. Here it suffices to note that the transfer system is probably the most critical structure of the TOD-metro complex. The actual final condition of it will define its own structural performance, but also the structural performance of the total structure. The challenges due to massive concrete concreting, the actual stress flow into the massive concrete joints, the post tensioning, and the laminated concreting make the structural monitoring an indispensable validation tool.

3.7 Noise and vibration issues

The train noise and vibration emissions due to the metro operation are a major concern for the near-by Real Estate developments in general. This is a highly specialized technical topic that deserves a dedicated presentation which unfortunately falls outside the main scope of this chapter. The main effort in this work is toward the more traditional structural analysis and design issues. It must be said however, that the TOD configuration dictates to a great degree the transmissivity of noise and vibrations coming from the operation of the metro. It is indeed very possible that the structural configuration as well as a wide range of material choices may be defined by it. Therefore, careful cooperation between architectural and structural design should incorporate also the noise and vibration transmission analysis.

It must be noted that the international experience shows that the vibration transmission can take place through the piles as well. Therefore, soil-structure interaction for the vibration transmission must take place.

The transmissivity of the vibrations through the station to the TOD is much different to the one from the tunnel to the nearby buildings, at the time of the tunnel boring. Therefore, even if there may be analysis and recording of measurements from the tunnel construction phase new measurements are necessary for the new compound structure TOD-metro.

The most widely accepted set of acceptance criteria is probably FTA Report *Transit Noise and Vibration Impact Assessment* [19] (see also [20, 21]) .

There are no effective mitigation measures known to amend a vibrations inflicted development a posteriori. The vibrations prediction must be complete and influence the structural/architectural design.

In general, a Finite Element model may be used for this. In some cases, the FE model is possible to play a dual role for structural-strength considerations and also for structural vibrations analysis. However, the discretization for vibrations analysis follows different and more stringent rules than the one for structural analysis. It might be practical however, to utilize the FE structural modeling for the vibration modeling as well.

3.8 Special geotechnical issues

The soil structure interaction may be so great that the structural effects could be savaging to the metro structural infrastructure. In **Figures 17** and **18** below the

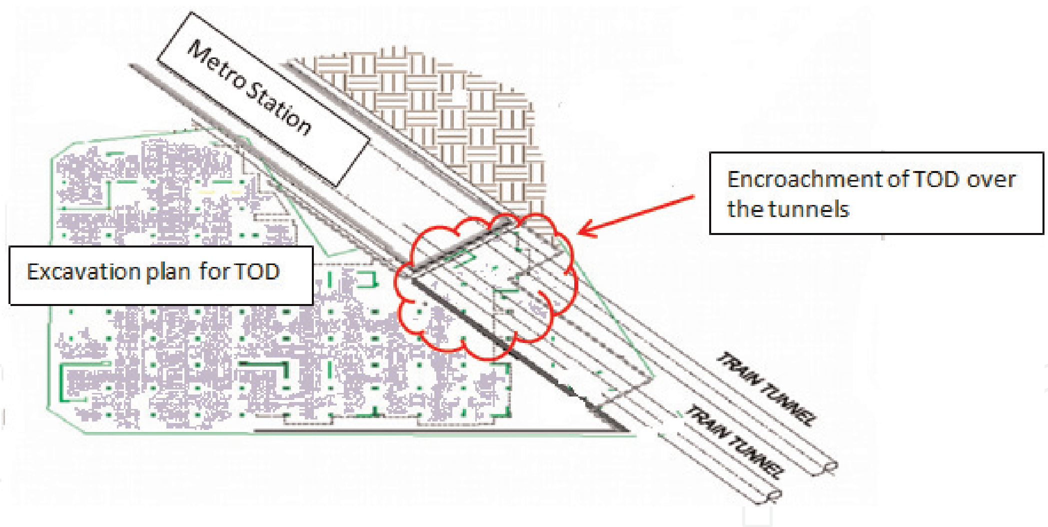

Figure 17.
Plan view of excavation next to the metro, station-tunnel. The unbalanced lateral earth pressures need to be considered for each construction phase.

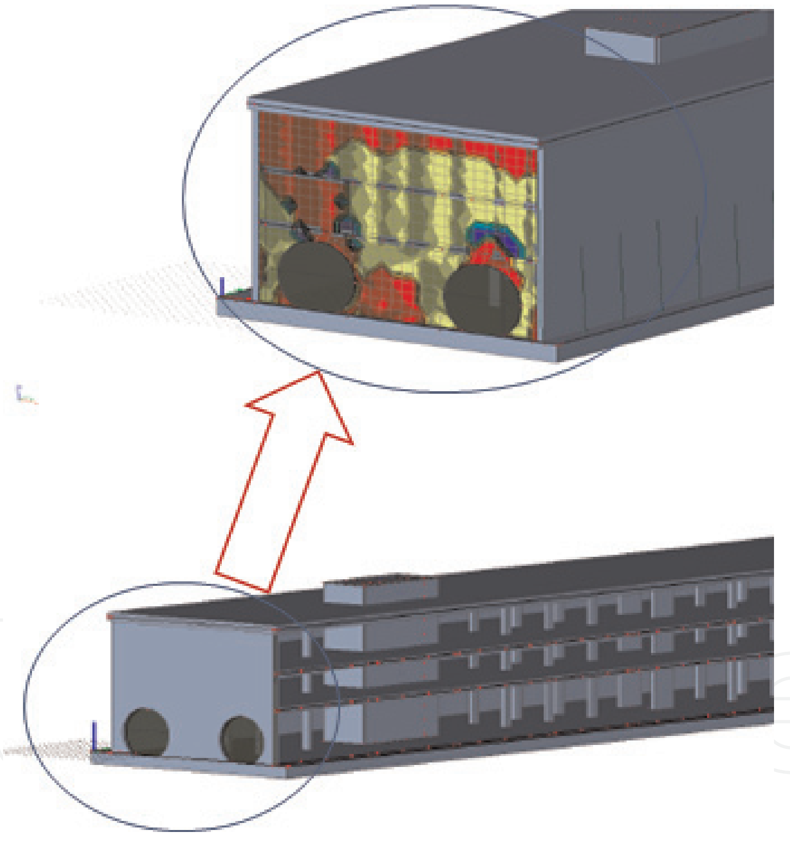

Figure 18.
Due to excavation only from one side of the station box, significant unbalanced earth pressures raise high stress distribution at the head walls. Other distressed areas include the column pier caps and the tunnel to station expansion joint displacements.

effects of the excavation next to the station concrete box have been analyzed to show the unbalanced lateral earth pressures significant effects. The otherwise resilient thick concrete shell walls of the station box are experiencing significant stress development which needs to be checked for the main failure modes (cracking—water ingress). Nonetheless, slender structural members like columns, need to be checked for their predominant failure modes, like buckling or punching through their pier caps. Due to the unbalanced earth pressures, an overall box torque-like

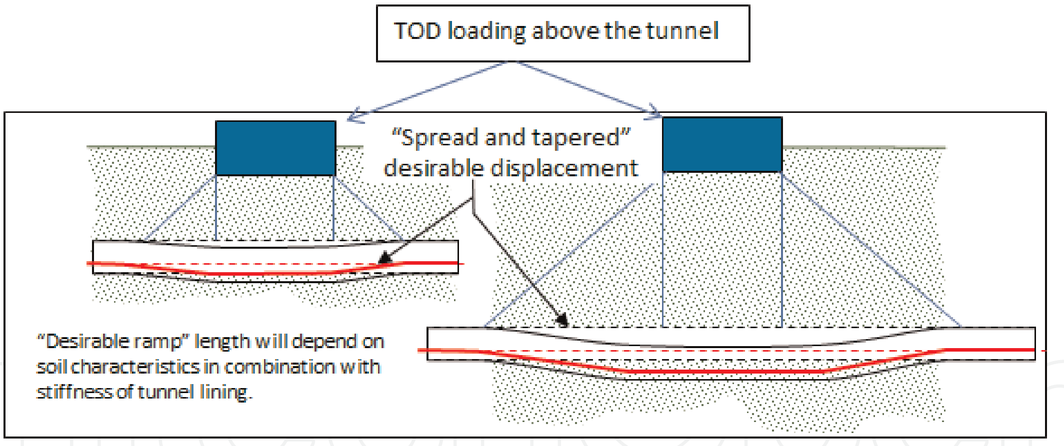

Figure 19.
Desired "ramping" of the displacements.

displacement field may is induced which, among other stresses, increases the bending moments at the pier heads, making the punching check more demanding.

Regarding the very sensitive rail track displacement issue, **Figure 19** is very depictive about the tight tolerances. In practical terms, the expansion joint opening tolerances may be limited to a tight 10 to 15 mm depending on the joint capacity and the waterproofing or gasket allowance. The allowable displacement envelope induced to the rail however is far more restrictive. Refs. [3–5, 7] sited in Section 2 should be considered regarding the rail displacement. However, the Rail authorities concern is usually, to grade the induced displacement to enough length. In general displacements of the order of 5 mm are tolerable, but the most important characteristic of the desired displacement profile is the spread over a significant length of the rail in order to achieve a tapered deformation profile (**Figure 20**).

Typical allowable requirements for the rail into the tunnel and at the expansion joints are displayed in **Table 2**.

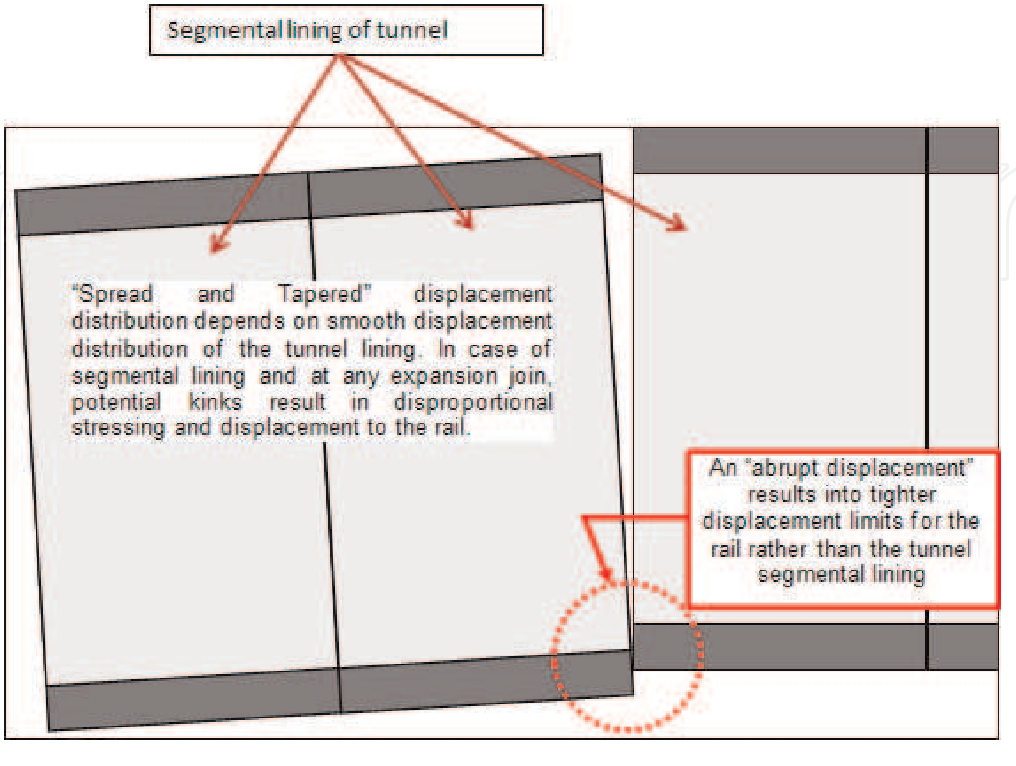

Figure 20.
The expansion joint opening tolerances may be limited to a just a few millimeters.

DOI: http://dx.doi.org/10.5772/intechopen.86923

Horizontal displacement of lining	20mm
Settlement of lining	10mm
Warning Level: Horizontal and vertical displacement measured on the rail	5mm
Alarm Level: Horizontal and vertical displacement measured at the rail	10mm

Table 2.
Suggested warning and alarm levels of displacements into the metro tunnel.

The tunnel concrete shell is highly susceptible to induced displacements because of any third party construction activities, let alone the TOD loadings. Moreover, the tolerances of the rail-track system are an even greater challenge. In contrast to the concrete shell which can sustain displacements of the order of 15 mm, the requirements regarding the rail are far more restrictive. Depending on the Rail organization, approximately, a mere 5 mm are tolerable and that should be spread over a span of 10 meters over the rail length (see for example [22, 23]).

At the interfaces of the Station/Switchbox—Tunnels, or any other type of expansion joint, there may be a sharp rise of differential displacements due to the TOD. Significant design effort must be put to make sure that the differential displacements of the rail are within the allowable limitations.

Furthermore, in the case of ring segmental tunnel, it must be preserved at all times in compression, in order to avoid tension cracks or unacceptable movements at the segments' interfaces. Therefore, significant effort should be provided in FE analysis to accurately detail the effects of the TOD on the tunnels and especially at the interfaces to the station. If piles are needed to pass close to the tunnels, significant effects are expected to the tunnels in terms of displacements and stresses. Single or double sleeved piles could be used in order to reduce the pile-soil friction and avoid stressing the tunnel to the degree possible. A comprehensive numerical study of the simulation of the sleeved piles in such cases can be found [24]. It must be always remembered however, that the friction reduction methods could not eliminate completely the friction, allowing therefore, a significant stress field to affect the tunnel or even the station box.

The arrangement of the foundation system of the TOD alongside the tunnels poses a significant challenge. In order to avoid stressing the tunnel lining or inducing unacceptable displacements, it often required to use pile skin friction reduction systems. The sleeved system offers a reduced pile skin friction but does not eliminate it. It must be remembered that it does not get reduced to more than 50% or maximum 30%. It is very difficult to verify what exactly has been achieved during the construction of the pile. Therefore, it is strongly recommended to follow a very conservative approach in the design, especially regarding the friction developed at the sleeved part of the pile. The vertical springs that simulate the friction should be appropriately treated in the model, while the lateral ones, which simulate the lateral resistance, should not be forgotten (**Figure 21**).

The pile cap will be a major source of bearing pressure to the soil, if in full contact, despite the axial resistance of the piles that they connect. Therefore, if a separation cannot be achieved, a cushion material should be designed and suitably inserted to detach the slab from the soil, as shown in **Figure 22**. This is not an easy task at all, either to design or to implement in construction. The degree to which this detachment is achieved is difficult to be verified.

Since there are so many sources of uncertainty, it may be wise to consider in the design envelopes of upper and lower bounds of induced stresses to the tunnel,

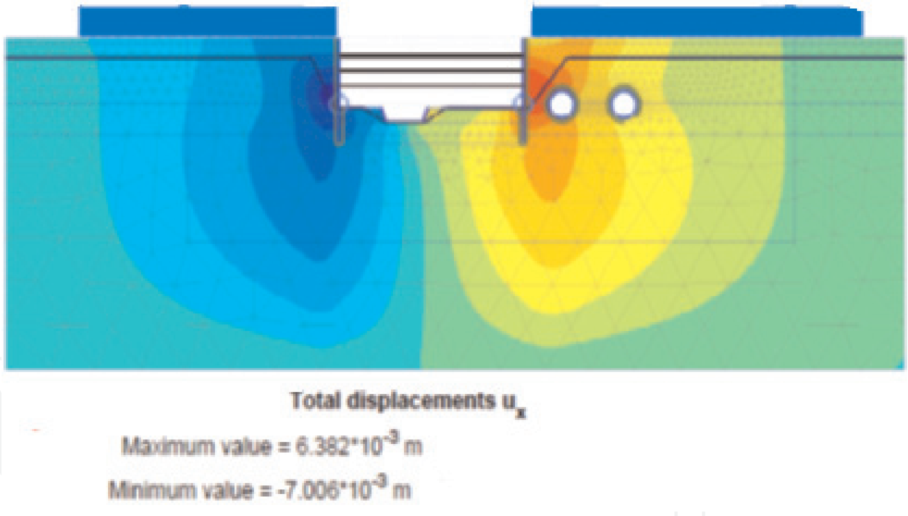

Figure 21.
Excavation for the TOD next to the tunnels. Experience shows that even at hard soils, like the Simsima Limestone of Doha, there may be significant displacements to the tunnels. And while the effects on the lining may be tolerable, the displacements to the track system may be prohibitive if no stabilization methods for the excavation are not in place.

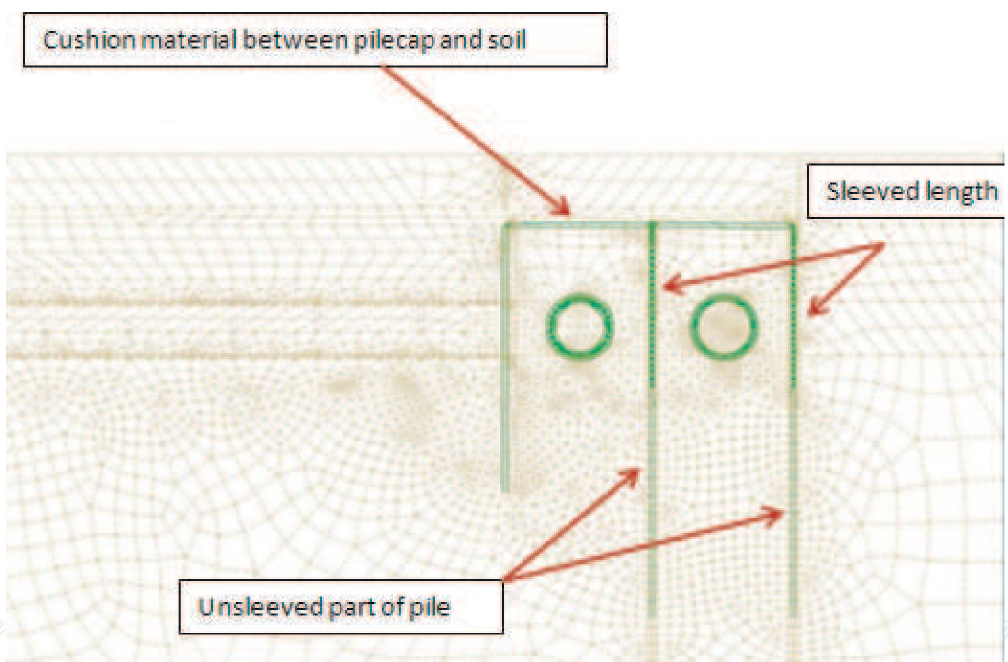

Figure 22.
FE analysis of effects of progressive excavation and TOD construction over the tunnels with segmental lining. As the piles are sleeved all the way down to the level of the tunnel invert, their representation into the FE model includes removal of the pile skin friction to a specific degree. This reduction is not suggested to be more than 30%.

representing the maximum and minimum friction sleeve isolation and soil pressure by the pile cap (**Figure 23**).

In **Figure 24**, a typical arrangement of geotechnical instrumentation as is shown. With such an arrangement it is possible to monitor the soil mass, and probably this may lead to reliable conclusions regarding the stress-strain conditions of the tunnel lining or the station (see also Refs. [25–27]). This can be achieved by comparing the readings of the instruments to the values of the displacement—stresses from the soil structure interaction analysis. But it becomes entirely indirect in the case of the more sensitive entities like the rail itself or even the expansion joints. In order to obtain the picture regarding the actual stress-strain conditions of the tunnel or the station it is important to have a direct instrumentation attached on carefully

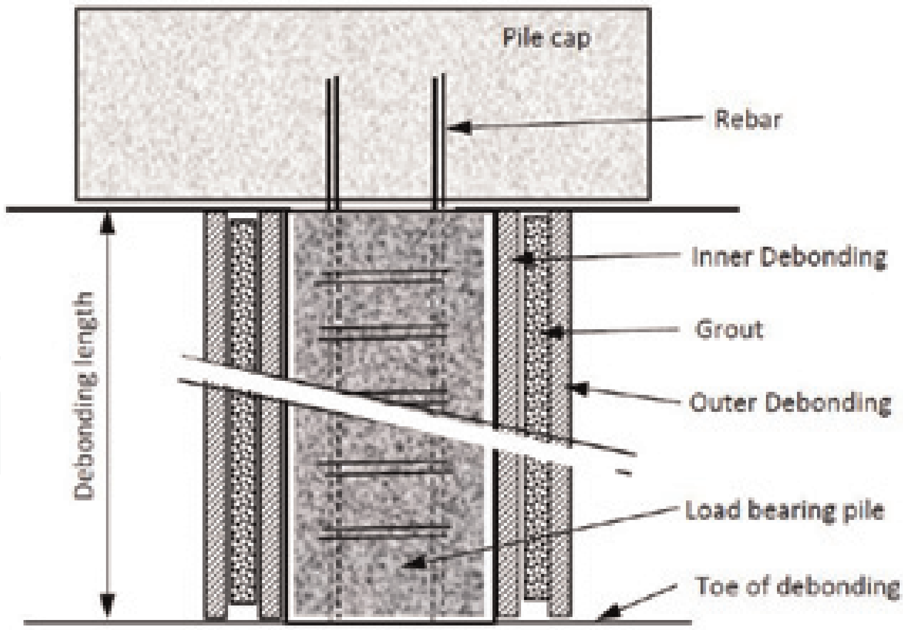

Figure 23.
Typical arrangement for pile debonding. Notice that the lateral support is not eliminated and should be considered in the simulation accordingly.

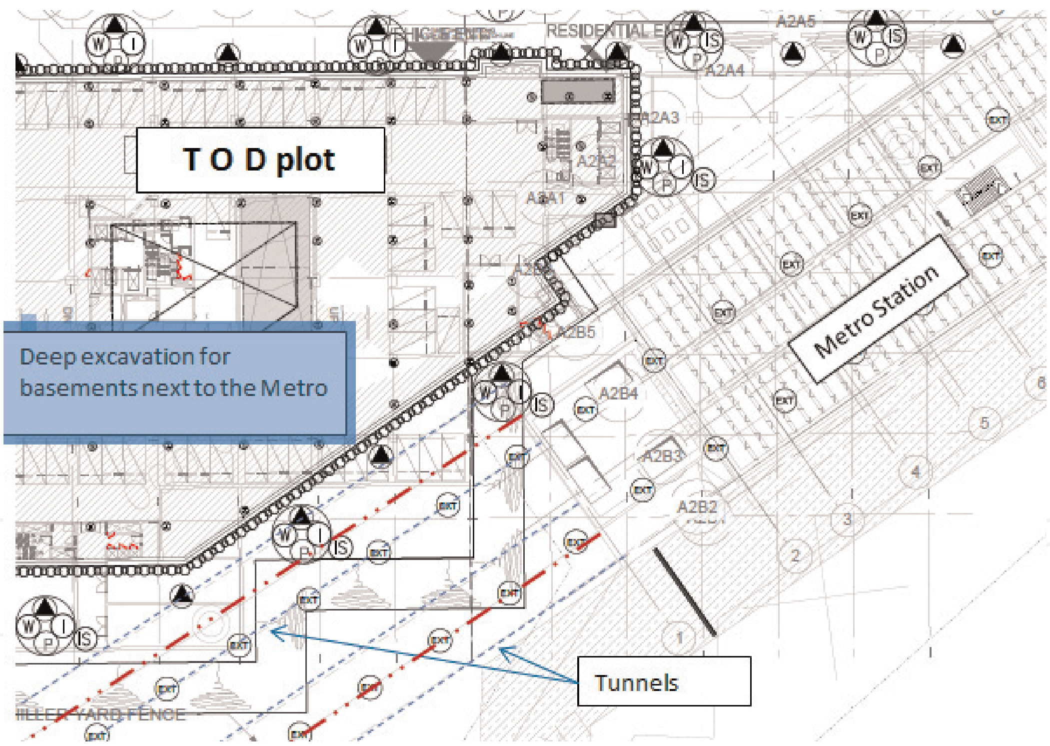

Figure 24.
Plan view of new construction next to the metro station and tunnels. A typical distribution of geotechnical instruments to monitor the surrounding soil of tunnel and station. Notation: EXT: extensometer, I: inclinometer, W: water pressure meter, P: piezometer.

selected positions into the structures. A more direct strain-stress distribution insight can be gathered from the instrumentation of **Figure 25**, where a fiber optic instrumentation is shown to "wrap around "the tunnel lining for a critical length. Such strain instrumentation is useful to provide the picture of the tunnel lining distortion at a critical are of interaction with the TOD or other third party construction activities. But the cost in this case becomes too high. On the other hand, if a mountable type of sensor is used, then the instrumentation can be retractable and is

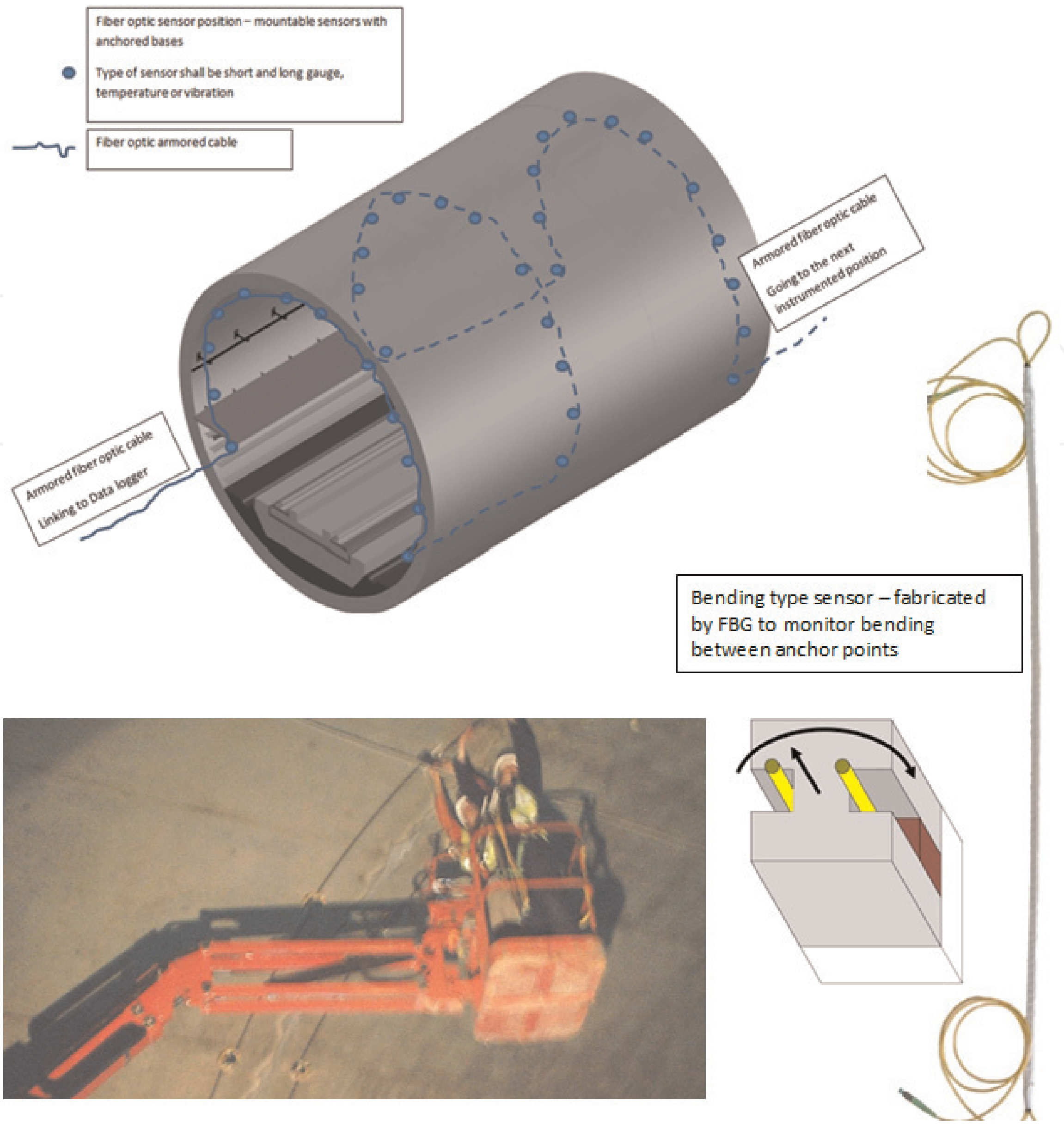

Figure 25.
The original FBG sensor, which is fabricated to operate in axial tension, has typically excellent characteristics in terms of accuracy and repeatability. When used into a compound sensor, to monitor other degrees of freedom (like rotation) may have dramatically reduced its fine characteristics. Testing and calibration are indispensable in such cases.

not "spent" in the specific section of the tunnel. It then can be used for a period of time to measure the effects caused and when requested can be transferred to another section. Only the bases to which the sensors are fixed are spent. The drawback in this case is the accuracy of the mountable sensor. It must always be remembered that intrinsic effects of the sensors are the gauge length, the attachment and the fixation, even the rotation of the attachment to the desired direction.

3.9 Structural monitoring

The structural monitoring of buildings although not entirely rare does not take place often. The experience built up until now is not comparable to the one of the geotechnical monitoring. A comprehensive presentation of recommendations and best practices can be found in Ref. [28]. It is the intention of this chapter though to support that structural monitoring is a necessary and indispensable part of the design of the TOD-existing metro compound. It is not an issue to be left to the contractor alone, as it seems to be a widespread belief. There are many reasons why the designer should specify the structural monitoring instrumentation and its monitoring targets. These include verification of critical design parameters (and how these evolve in due service life time) and construction loading parameters which affect the existing metro structures and for which there may be many unknowns. In general, in the consideration of the compound TOD-metro structure there is accumulated significant uncertainty mainly due to the long assumptions list for the behavior of both parts but more importantly of their interaction. Tolerable displacements of each part of the compound structure may mean significant change in the boundary conditions of the other part. Moreover, the interface between TOD and metro, as configured in the transfer systems may have itself significant uncertainty built up. To give a few examples, concrete deterioration of the transfer slabs or girders may mean not only reduced service life of the members themselves or of the TOD but also altered reaction envelope for the metro, which receives them. Reversely, concrete deterioration of the metro may ignite change in the boundary conditions for the TOD. Concrete deterioration may be of limited or controllable character for the structural member itself, but may produce disproportional alteration to the stress distribution over the TOD-metro compound.

Exactly because such reaction changes at the interface of TOD-metro due to any damage accumulation or structural performance are unpredictable it is necessary to monitor the condition of the critical structural members. The transfer systems in this endeavor are high in the priority list.

The nature of the transfer systems makes the employment of advanced monitoring instrumentation necessary. The target of the monitoring should be the validation of the stress-strain levels, the displacement field and also the structural condition of the members monitored. In order to make possible to synthesize the stress-strain gradient picture throughout the total section of the member the instrumentation should have robust characteristics (**Figures 26**–**28**).

- Robustness and redundancy of sensors: As a basic rule, it's highly preferable to have not only robustness in the sensing systems but also redundancy of the sensors, despite the additional costs. Potential damage of the cabling of the sensors during the construction shall reduce drastically the life span of the instrumentation. Therefore, significant budget for SHM is dedicated to cable protection in the form of conduits, extra protection for cable splices, sensor

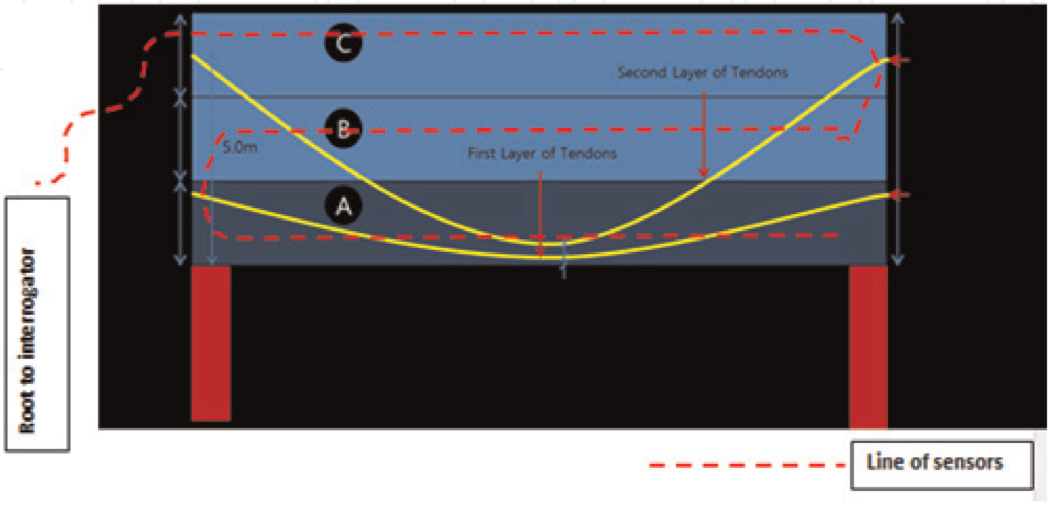

Figure 26.
A triple layer construction sequence envisaged for thick slab transfer system of a TOD over the metro tunnels. Note the post tensioning tendons and proposed arrays of strain-thermal sensors.

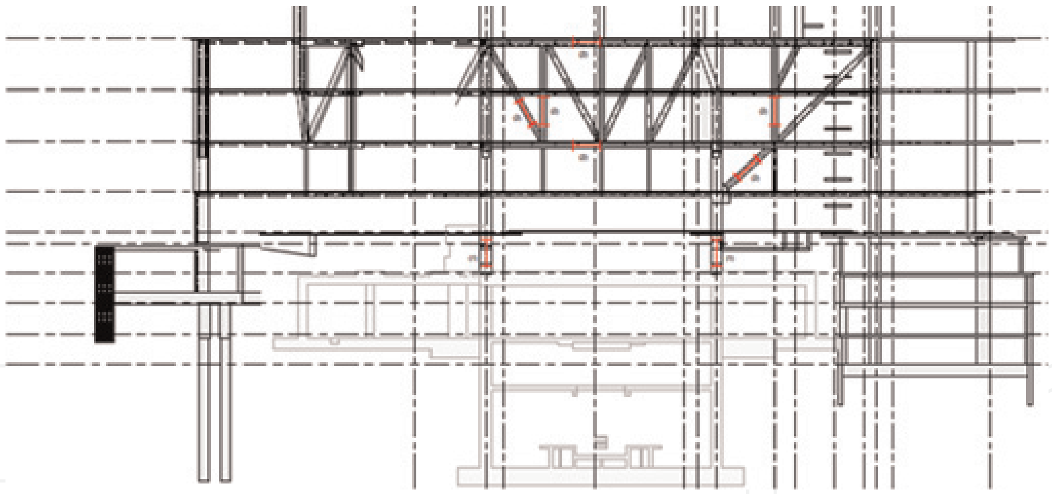

Figure 27.
In this transfer steel truss system the members marked with red symbol are of greatest concern to the designer. He therefore designed a strain monitoring system to validate the stress-strain development during the erection of the structure and building up of the loads.

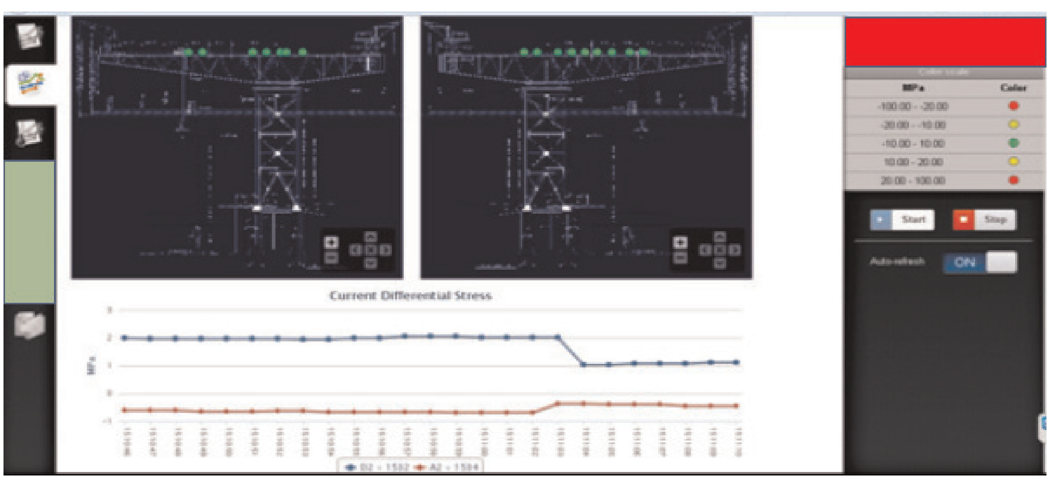

Figure 28.
A situational awareness visualization tool is necessary to obtain the overall picture and the same time to be able to locate on the BIM the section of interest to get the sensor analysis in detail. In the figure each green dot on the top of the structure represents a set of two sensors. Their stress flow history is shown in the bottom of the screen. On the right hand side of the screen their stress analysis level is compared to the green-to-red chromatic scale of alarm.

covers, etc. Moreover it's highly recommended to pass alternative or additional cable routes with redundant sensors at least at the most critical members/areas.

- Complementarity: For the sake of validation, complementary verification systems should be specified in order to verify the results and validate the method. (E.g., strain sensors should be complemented by displacement sensors and if possible with vibration monitoring, displacements complemented with pressure cells, etc.)

- Coverage of the area of interest: Orthonormal grids of sensors are recommended to be installed. They should follow the principal stress flow in surface elements. In case of line elements (columns-beams) multiple sensors should be employed for monitoring the rotation of neutral axis.

- Inspectability of the system: In all cases, appropriate armored conduit should be used, especially in the cases were the cables are exposed and not within the structural member.

In order to achieve such characteristics, the designer should specify wisely the instrumentation characteristics. Parameters to be considered should include:

- Specify the stress range
- Specify the gauge length
- Specify the Degrees of freedom of the sensor
- Specify the attachment method and stiffness of the attachment in relation to the substrate
- Specify the cover of the sensor

Investigate:

a. The Modulus of Elasticity of the structure

b. Temperature compensation

c. Moisture and drift

At the sensor points a member cross section analysis can be performed to provide the distribution of stresses and strains to compare with the monitored strain distribution. It follows that careful positioning and attachment of the sensors is necessary. In order to obtain a clear picture of the stress condition of the structural member and the notional rotation of the neutral axis it's rather necessary to use more than one sensor at every cross section.

A significant part of the structural monitoring, which deserves separate analysis is the corrosion monitoring. Corrosion of reinforcement and especially of tendons is critical concrete deterioration which must be early detected and mitigated. Instrumentation for corrosion monitoring may in some cases be combined by cathodic protection infrastructure as shown for example in **Figure 29**. The inspection port is meant to be used for incipient current cathodic protection. Otherwise, separate apparatus may be installed. This may be comprised by embedded half-cell potential wiring, reference electrodes, or chloride ingress detection devices. The risk of corrosion of the post tension tendons is especially high in structures close to the ground and to ground water. In regions where the soil is rich in chlorides like in the Arabic Sea states, even underwater there is significant prospect of corrosion, through formation of macrocell development. This is noted to happen in underground heavily reinforced concrete boxes of stations and switchboxes (see also [29, 30]). Macro cell corrosion, where the cathodic reaction taking place in an aerated zone of the structure and the anodic process taking place the depassivated area may produce non-expansive products making the phenomenon undetected until it will be too late. This has been found to be occurring in cases of post tensioned tendons and especially when the duct grouting is problematic.

Active corrosion protection is by far a more prudent way to secure the Design Service Life of the structure. The high costs for distributed anodes or incipient current protection pay off as a major concrete deterioration risk is removed. The hybrid type of anodes has shown excellent characteristics while they offer the advantage of periodic chloride ion removal (see also [29–32]) (**Figure 30**).

The application of such a method for active cathodic protection all over the foundation system of the TOD may be very costly. The critical structural elements however, should be seriously considered to be protected, especially when post tensioning is present.

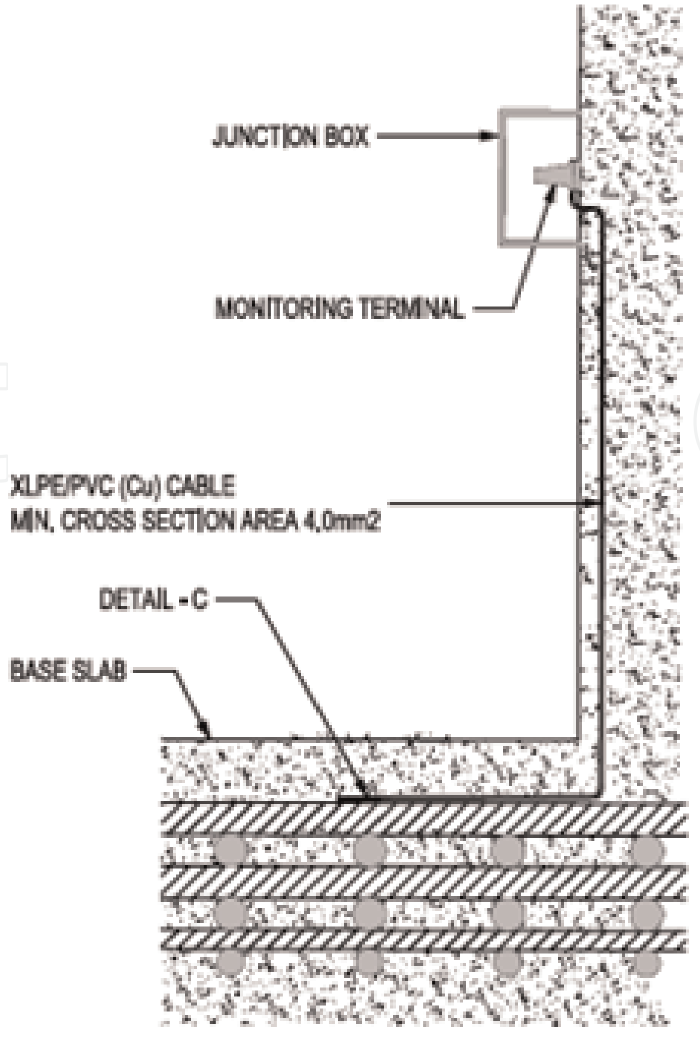

Figure 29.
Cross section of base slab to lining wall concrete joint. A monitoring terminal is shown. It is used for connectivity check, but can in theory serve for corrosion monitoring and incipient current.

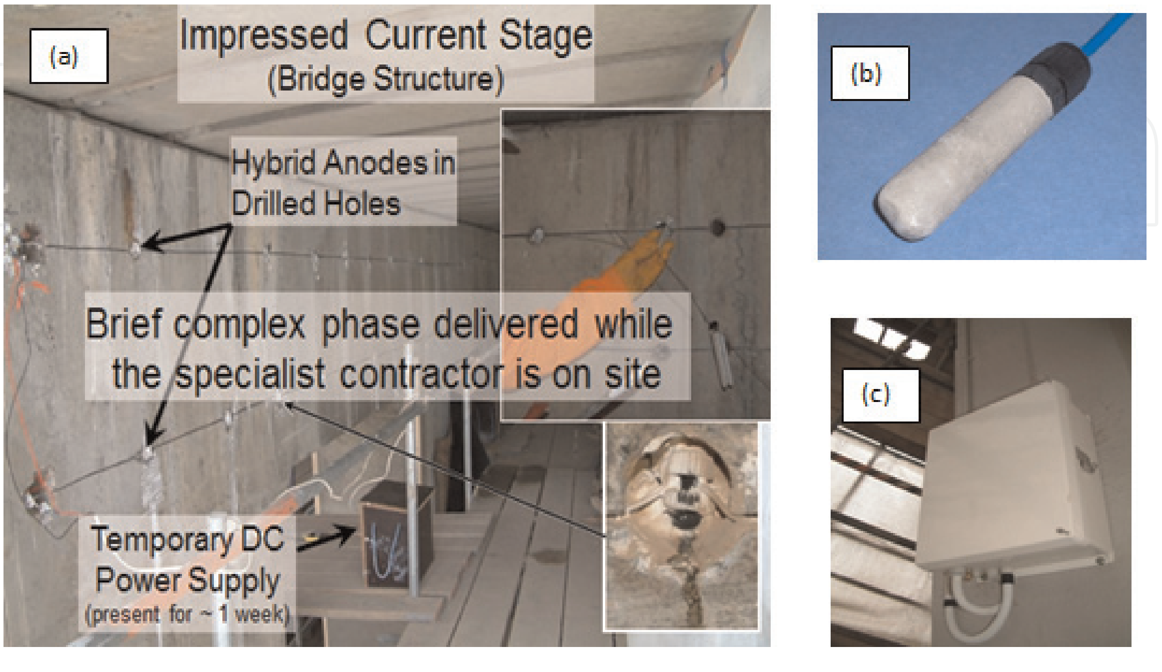

Figure 30.
(a) Distribution of hybrid anodes, (b) reference electrode, and (c) transmitter for remote sensing.

4. Verification, validation, and uncertainty quantification

From all the major points discussed in the preceding sections of this chapter it must have been evident by now that the structural compound of the TOD and the metro is a highly complex system. It is a complex system in the sense that it presents emergent properties: i.e., properties that are not apparent from their structural members when these are studied in isolation but which result from the relationships and dependences when they are finally constructed [33–36]. The assumptions log of the total structural analysis is being increased too much because of the interaction of structures and structural elements so different to each other. The predominant Failure modes of metro are different when the TOD is built over it, as the ones of the structural elements of the TOD when considered on a fixed foundation rather than on the metro. The displacement limits of the rail-track measured at millimeter scale are in significant contrast to the large scale Finite Element model of the metro-TOD compound which produces so great reactions in magnitude, has enormous computing requirements, it has many assumptions pertinent to large scale structural systems rather than the one comprised by the delicate rail-track system. Let alone the inherent uncertainties regarding the existing metro structural condition. The same time there are critical structural elements like the transfer systems that require a thorough verification of their functionality.

In order to keep the Uncertainty contained in acceptable levels, a rigorous Verification and Validation system is necessary to be employed. A far as design is concerned, it should not focus only on producing reliable simulations, in terms of Finite Element analysis and BIM, but it should focus on accumulation of evidence of the credibility of the simulation results. This should be an important element of the risk management plan for both the TOD and if possible of the metro.

It is asserted in this chapter that the laboratory testing of critical structural members and also data collection from structural monitoring are vital parts of uncertainty quantification procedure and that validation is achieved through compound simulation, testing and structural monitoring.

As has already been said in Section 3.6, mock up tests for concrete are very important. Mock ups of massive concrete would provide information about the actual heat dissipation flow of the specific concrete mix to be used. Strength build up, thermal gradient and thermal stressing are vital pieces of information that are needed for the most critical structural members of the TOD, like for example the concrete transfer slabs or girders.

Unfortunately, the uncertainty regarding the performance of them is deemed to built up with the size (not only the thickness), the reinforcement quantity, concreting conditions, weather conditions, concreting layers, construction joints, post tensioning and stress flow into the joints. Therefore, a good solution to cast light into all these complicated and intrinsic procedures, series of laboratory tests could be organized. The same time, data collected from structural monitoring are necessary to provide the picture of the actual developments of the monitored parameters.

A great benefit would be to identify the failure modes of the transfer systems. The laboratory testing should focus on each failure mode and organize precautions for them. The precautions should have the form of simulation calibration parameters for further analysis during the final Detailed Design phase, construction, construction sequence, maintenance and monitoring during the service time.

The risks from concrete casting in layers should be investigated. Thermal issues, de-bonding and post tension passing through the layers should be thoroughly studied. Again, guidelines for the casting and tensioning should be drafted.

The key attributes of simulation credibility are evidence of completeness and correctness, which must be communicated in an understandable and straightforward manner. In conjunction with simulation governance, the technical processes to build and assess correctness in simulations are verification, validation and uncertainty quantification.

This issue should be closely monitored with the structural monitoring means, to cast light in areas that will be critical in the actual TOD behavior.

The scope in this case of monitoring is not only the ultimate capacity, but also potential deterioration/change with time, as this would inevitably lead to magnified effects on the rest of the building or even the QR assets (stations-tunnels). Therefore and because of the massive concrete character of the transfer system, a well-studied instrumentation strategy needs to take place. The performance of the instrumentation depends on the position of the sensors, the type of the sensors, the attachment method and many other factors. Fruitful results will lead to decisions about complementarity of the sensing systems, redundancy, accuracy of local measurement and overall structural response.

The simulation results are thus compared with sub-scale systems or portions of the complete system, such as subsystems and components of the total system. Formulation and approximation errors are commonly intertwined with uncertainties in the input data for the mathematical model. If for example, initial conditions, boundary conditions, or system parameters cannot be measured independently, then uncertainties in these quantities are entwined with model formulation and approximation errors. Therefore, model calibration becomes necessary. As a result, model parameter calibration and model validation involve an iterative process for cases where experimental data and data from structural monitoring are available. A potential procedural flow chart for Experimental and numerical simulation cross validation is shown in **Figure 31**.

There is one more thing however to consider regarding the VVUQ. This has to do with the method of the structural analysis itself. In order to utilize the VVUQ character described in the previous paragraph, it may be found practical to perform types of analysis resembling to Failure Mode and Effects Analysis, or even Fault tree analyses. This has to do of course with the critical structural members, the load paths utilizing them, and potential alternative load paths. A good paradigm of such approach is offered in Refs. [37, 38].

Ordinary structural analysis as ruled by international standards, (like the Euro Norms—EN1992 for example), does not categorize the structural members depending on their importance. It does not categorize or classifies potential failures, as the aim is to avoid either.

However, some structural elements are apparently more critical, or their integrity may be vital for the whole structure. Obvious examples in the case of the metro-TOD compound are the rail-track system and the transfer slab/girder respectively. But the complexity of the compound structural system pronounces the criticality of other structural systems as well. For example, a long span post tensioned beam is far more critical and should obtain a higher degree of structural importance than an isolated beam at a part of the structural system with large structural redundancy. Or equally, and to put it closer to the FMEA, a potential failure of a structural member that leads to progressive collapse is more important and deserves higher severity ranking than a potential failure of a structural member that will cause moment redistribution achievable by a robust and highly redundant structural system. The predominant failure modes of the transfer system of the TOD should be examined thoroughly from the perspective of progressive collapse, activation of alternative load paths, limitation-containment of collapse/failure and especially, away from the Station box and tunnel and at least away from the rail-track system. Obviously, the

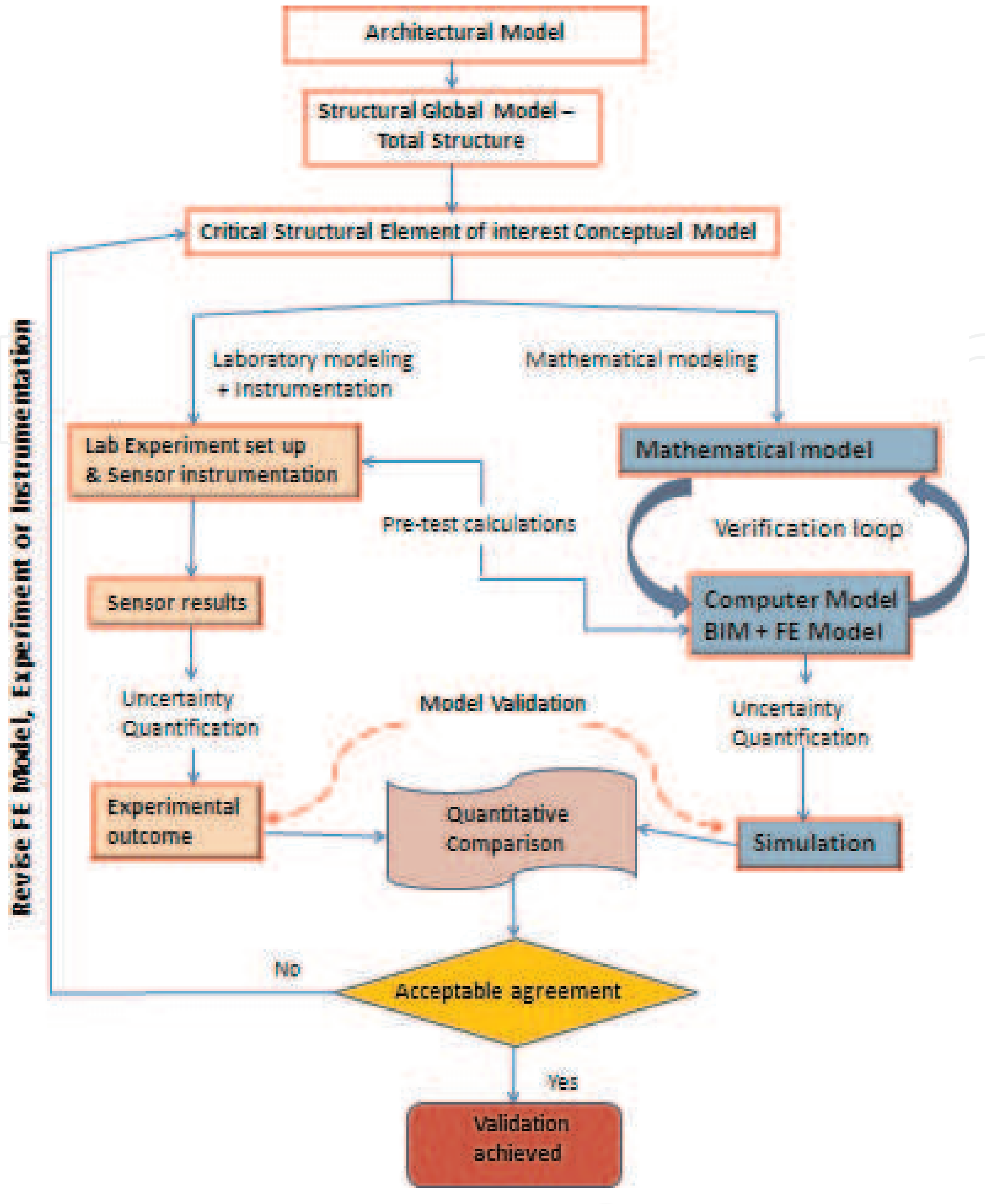

Figure 31.
Flow chart for cross validation of experimental and numerical simulation.

hierarchy of structural assets leads to prioritization of failure mode analysis and effects analysis.

In a potential FMEA there should not be a limitation only to controls for the typical Ultimate and Serviceability Limit states. Durability deterioration should be included in such investigations as well. Potential introduction of importance factors attributed to structural members should take into account the risk factors for damage or failure: Occurrence, Severity and Detectability.

5. Conclusions

This chapter is an effort to provide a glimpse of the multi-faceted design efforts for analysis and design of transit-oriented developments over existing metro structures. It has been pointed out that the existing metro stations and tunnels are very sensitive structures with very tight limitations for the displacement and stress envelopes induced by the TOD. The Structural interventions needed to accommodate the transit-oriented development must be considered following a comprehensive structural assessment of the existing structures. The effort needed to model properly the combined TOD-metro structure is very significant. Careful procedures should be adopted for the modeling of the boundary conditions of the two distinct parts and of all critical structural members. Special Finite Element—numerical treatments should be employed to approximate massive concrete. The importance of the Transfer system is highlighted, along with the potential detrimental factors that may affect its performance and that need special attention. The combined TOD-existing metro structure has got a long assumptions log which makes inevitable the structural monitoring and active corrosion monitoring and protection. The structural monitoring should be also considered as a vital tool for the validation of the design and construction assumptions and procedures.

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