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Grade A Office Space in Mexico City: Tight Sites and Shaky Ground

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Abstract

In recent years Mexico City has seen a surge in tall building construction, concentrating around the new Central Business District on Paseo de la Reforma, and culminating with four new skyscrapers clustered at its west-central end. Arup has led the structural engineering design of three of these towers as well as Torre Pedregal 24, a striking new office building a few miles away. These buildings have been designed using innovative structural solutions to provide Grade A office space in this highly seismic zone. This paper will provide an insight into their design and the unique challenges that building tall in Mexico City presents.

Once completed, the four towers: Torre BBVA Bancomer; Torre Reforma 509; Torre Reforma; and Torre Pedregal 24, will provide over 200,000m2 of prime office space overlooking the impressive Chapultepec Park.

Keywords: Office; Performance Based Design; Seismic; Structural Engineering

An introduction to Mexico City

Mexico became an independent republic in 1823 with Mexico City as its capital (Connolly 2003). Throughout the 20th century, the city grew in population and importance; by 1980 47 percent of all Mexican manufacturing was located in Mexico City. However, trade liberalization during the eighties saw this drop to 17 percent by 2003 as employment in the city shifted to the service sector (The Brookings Institution 2013).

Today, the Mexico City metropolitan area is home to over 20 million people and has the eighth largest urban economy in the world. 63 percent of its GDP stems from the service sector and nine of the top 10 Mexican exporters have their headquarters in the city (The Brookings Institution 2013). The city's central business district has also become a focus for international investment; in 2010 Mexico City received $13.5 billion in foreign direct investment, 70 percent of the total investment in the country (The Brookings Institution 2013).

The past few years have seen a significant number of new commercial developments. While current rental values peak at $35 per sf/yr, about half those in Manhattan, there are currently over one million square meters of office space under construction, twice that in Manhattan (Cushman & Wakefield 2015).

Much of this development is concentrated in the new Central Business District on Paseo de la Reforma, culminating with four new skyscrapers clustered at its west–central end. Arup has led the structural engineering design of three of these towers from their London and New York offices, as well as Torre Pedregal 24 (also known as Torre Virreyes), a striking new office building a few miles away. All four buildings have been designed using innovative structural solutions to deal with the constraints posed by this unique metropolis. Each tower is unique to the requirements of their client, however a number of themes remain constant through their development – these are explored over the following sections and introduced in Table 1.

Dealing with Constraints

As an historic capital with a well-developed center, there are few available sites within Mexico City. Developers, seeking to capitalize on the city's expanding commercial market, are therefore forced to acquire existing buildings in locations zoned for high rise construction but occupied by low rise buildings. Consequently, high rise building construction in the city is often located on a small or irregular site. Adjacent roads, underground infrastructure and neighboring construction all create additional constraints.

Project Name	BBVA	Torre Reforma	Punta Chapultepec (Reforma 509)	Pedregal
Client	BBVA Bancomer	Fondo Hexa	T69	Grupo Danhos
Architect	LegoRogers (RSHP+Legoretta)	Benjamin Romano Associados	Taller-G	Teodoro Gonzalez DeLeon Arquitectos
Local engineering partner	Colinas de Buen	DITEC S.A. de C.V.	DITEC S.A. de C.V.	DITEC S.A. de C.V.
Use	Office, Commercial	Office	Office, hotel, residential	Office
Superstructure height	234m	246m	238m	132m
Above/below ground levels	52/7	57/10	58/12	25/16
Total Floor Area	108,000m2 above grade	75,000m2	70,000m2 above grade	130,000m2
Primary structural system	Eccentrically Braced steel Frame. No concrete core. Steel columns.	Coupled Shear Walls + perimeter braces	Concentric braced steel frame. No concrete core. Composite (SRC) columns.	Concrete core + perimeter steel 'V braces'
Expected completion date	2015	2015/2016	2017/2018	Complete

Table 1. Overview of case studies referenced throughout this paper. (Source: Arup)

One of the most dramatic examples of this was encountered during the design of Torre Reforma. The new tower is developed on a site occupied by an historic two story masonry hacienda (house). The existing building acts as a key driver for the developed building geometry. The tower's architectural form is developed as a right-angled triangle in plan composed of concrete shear walls on the legs of the triangle, and a glass façade along the hypotenuse providing dramatic views out to Chapultepec Park. With iconic double-V bracing along the glass façade, the building spans above the existing hacienda hanging the floors by the V-braces back to the corners of the shear walls.

During the construction of the building's basement and foundations it was necessary to temporarily shift the existing hacienda from the south-west corner of the site to permit the placement of diaphragm walls that would serve both as the foundation elements of the building and retaining structure for the top down excavation. The temporary relocation of the building involved underpinning of the existing structure and placement of supporting panel walls to facilitate the placement of roller jacks. This was designed in collaboration between DITEC, the Mexican structural consultant, and Arup. The house was shifted approximately 40m north of its initial position, and restored to its final location after the remaining panels were constructed below the structure, see Figure 1. The complete structural system remains fully intact and the interior architecture is to be refurbished to meet the new program requirements of the space.

Figure 1. The historic house at the foot of Torre Reforma was moved 40m during construction (Source: Arup)

24 Pedregal is also constrained by a historically protected building at ground level. The new tower, defined geometrically by its east and west office wings, slopes above the existing Vladimir Kaspe Building achieving a 75m cantilever at the highest levels Figure 2. The two wings of the building have different dimensions at the base and gradually slope inward toward each other to meet at the top story.

Unlike most urban centers, the Mexico City Building Code imposes significant requirements on the amount of parking required for commercial buildings (approximately 1 space per 30m2). This created a key constraint for all four of the towers, with a different solution developed for each one.

At 24 Pedregal the complete requirement was met in a traditional underground car park. However the narrow site required 16 basement levels to comply with code requirements without impacting above

Figure 2. (Left) the impressive 75m cantilever at 24 Pedregal protects the existing Vladimir Kaspe Building. (Right) Pedregal's 16 story basement – the deepest in Latin America (Source: Arup)

Figure 3. The ground floor of Reforma 509 has no internal columns allowing passenger drop-off and facilitating mechanized parking below ground. (Source: Arup)

grade space demands. At 55m in depth, it is the deepest commercial basement in Latin America and to the author's knowledge, the world.

Soil conditions vary significantly in Mexico City; dramatic differences were encountered between 24 Pedregal and the remaining towers, despite being within 3.5km of each other. Soft soils on Paseo de la Reforma restricted the depth of basements that were feasible and so alternative solutions were developed for excavation support.

Reforma 509 is located on a site so narrow that it is difficult to imagine a high-rise building in its location. At only 25m wide, the site is constrained by a public street and underpass on one side and Torre Mayor on the other. Achieving the required car parking and circulation for the office, hotel and residential uses, combined with commercially competitive structural efficiency, was a huge challenge.

Twelve shallow stories with mechanized parking below ground, and four stories of parking above ground leave the ground floor largely open for passenger drop off, with entrance lobbies for offices, hotel and residences at an elevated floor accessed by escalators Figure 3.

The open ground floor plan, changes in building use over height, and top-down construction meant that a heavy concrete core was not suitable for this building. Indeed, the ground floor is completely free from internal columns. Superstructure building floors span efficiently with standard rolled steel sections, with central column loads transferring to the building perimeter at Level 16. This not only enables column-free spaces, but shifts gravity load to the perimeter where it reduces tension demands in the columns and provides structural material in the location where this generates the greatest resistance to overturning.

Across the road at Torre BBVA Bancomer, the main tower shares a common basement with a parking ramp and annex structures. In order to comply with the parking requirements, extensive parking and circulation was required in the tower footprint, not only in the basement, but also in the lower section of the superstructure. Consequently the office accommodation starts at level 14. This challenged the design team to consider solutions beyond a traditional concrete core, which would have been highly restrictive for vehicle circulation in the lower portions of the tower.

Mexico City has a subtropical highland climate where the temperature rarely goes outside the range 3°C to 30°C. This benign climate enabled the entire lateral system to be positioned outside of the building's thermal envelope, allowing architectural expression, uninterrupted floor plates, and maximizing its effectiveness in resisting lateral loads. The steel frame solution helps reduce the seismic weight of the tower and the associated foundation loads. It also provides an interior that is largely free of structure. The absence of a concrete core enabled the architect to terminate the primary elevator core at Level 11. Below this level, the floor plates are open, maximizing the net usable area of the tower.

Collaboration - An Imperative and Inspiration

The rapid growth in construction in Mexico City creates an intersection, not just between new and old buildings, but between local and international professionals. All of the projects presented here relied on teams spanning cultures, continents, languages, and professions. As with the best relationships, many of these have been complicated, lengthy and forged through hard work. However, none of these buildings would exist without the diversity of experiences and perspectives that characterize their teams.

For BBVA Bancomer, structural engineers from Arup worked alongside the building's architect LegoRogers, a joint venture between Rogers Stirk Harbour + Partners (London, UK) and Legorreta+Legorreta

(Mexico City), to develop a structural system that provides excellent seismic performance and architectural freedom in space planning and expression.

A clear lateral structural system was developed at the competition stage of the design, and this was maintained through to construction. The system comprises an external megaframe with six perimeter columns, continuous eccentric bracing on the four orthogonal sides of the building, and intermittent eccentric bracing on the two shorter sides of the building. The structural system is described as an Eccentrically Braced Megaframe (EBMF) and is the first of its kind to be constructed, Figure 4.

The design team's integrated approach to architecture and structure has produced a unique system that maximizes the developable area of this prestigious location. Through the application of a clear design strategy and sophisticated analysis, the project provides the client with an iconic, yet efficient building.

Torre Reforma was developed in collaboration with the Mexican architectural firm L. Benjamin Romano Arquitects (LBRA) and with the local structural engineering firm DITEC. This team leverages local architectural practice and local understanding of construction experience along with an international design approach. These three firms worked together to develop the double V-brace system that completes the torsional and lateral resistance of the building and maximizes views from the office space.

Additionally, the use of long span pyramidal floor trusses provides opportunity for integrated structural and Mechanical Electrical Plumbing (MEP) ceiling packages and creates a column free office plan. The trusses maximize efficiency in comparison to conventional composite rolled framing and minimize the number of crane picks during construction.

For Reforma 509 the structural design was undertaken by Arup in London in collaboration with Mexican architects Taller-G, Mexican structural engineers DITEC, and developers Lend Lease. The aim was to maximize prime office, hotel, and residential accommodations on a narrow strip of land where Paseo de la Reforma meets Chapultepec Park. From the outset of the project, structural efficiency and constructability was a key driver for this exceptionally slender building with stacked functions. A strong collaborative spirit enabled effective design refinements that surpassed the client's structural efficiency targets.

Figure 4. Torre BBVA Bancomer uses an Eccentrically Braced Mega frame to provide lateral stability and flexibility of floor planning. (Source: Arup)

Figure 5. The V brace at 24 Pedregal (Source: CAMILA COSSIO)

Working in Collaboration with Teodoro Gonzalez DeLeon Arquitectos and Grupo Danhos, the developer, the target of the structural design of Torre Pedregal was to achieve an architecturally ambitious building at competitive construction costs. To address this, Arup proposed to eliminate non-essential elements of the existing diagrid scheme, maintaining only the elements critical for the load path. This led to the V-brace configuration that now dominates the architectural design of the building. By moving away from a moment frame or diagrid system, the facades achieve much greater transparency allowing panoramic views of Chapultepec Park to the east and Lomas de Chapultepec to the west. This scheme also created a column free lobby and open floor plates ideally suited to a commercial office development, Figure 5.

Providing Performance

Mexico City is located on a high volcanic plateau, 2240 m above sea level. The Basin of Mexico, where the city now stands, previously contained a number of lakes which have been drained to allow the City to develop. Although the lakes have sunk from view, water extraction has continued. As a result, the soft soils in the city are settling at up to 200mm per year.

The unusual geological features of Mexico City, combined with its proximity to the Circumpacific Belt, the highest seismicity region worldwide, create an extremely onerous seismic hazard. To the west of the city along the pacific coast, the Cocos plate subducts beneath the North America plate at a rate of 50-70mm per year. This plate boundary is the primary source of large earthquakes in the city including the worst natural disaster in Mexico City's history. The 1985, magnitude 8.1 Michoacan earthquake caused over 10,000 deaths in the city and left an estimated 250,000 homeless. The impact of such a recent disaster has created heightened seismic awareness within the city; particularly amongst developers, architects and engineers. Seismic performance is consequently a key technical and commercial driver for new construction in Mexico City.

The four Arup high-rise projects use a combination of Mexican code requirements and Performance Based Seismic Design approaches to deliver buildings that are locally appropriate and consistent with international best practice designs for tall buildings.

While the precise requirements for each project varied to reflect client needs and site locations, the overall objective of the Performance-Based Seismic Verification was to establish a detailed understanding of the seismic hierarchy and behavior of key elements, such that holistic seismic performance could be demonstrated for the most economical and flexible structural solution. Typical performance objectives were:

- Demonstrate essentially elastic performance during service-level earthquakes.
- Verify strength and deflection demand for code level earthquakes.
- Demonstrate life-safety performance at Maximum Considered Earthquake (MCE).

The primary framework for the Performance Based Seismic assessment was the Pacific Earthquake Engineering Research Center (PEER) Report 2010/05 and ASCE 7-10. Non-Linear Response History Analysis (NLRHA) was completed using earthquake records spectrally matched to the site hazard, using the approach set out in Grant et al. (2008).

NLRHA comprises a structural representation of the building, with non-linear properties for the elements that are intended to go beyond elastic behavior. This structural representation is then subjected to ground motion records applied at the base and solved in the time-domain to give the transient dynamic response of the structure. LS-DYNA was used for the NLRHA on all of the projects presented here.

Conventional response spectrum analysis does not predict the cumulative plastic strain demand in yielding elements. This is a particular concern for the long duration ground motions that are characteristic of Mexico City seismic hazards. Furthermore, the representation of the modal interaction and distribution of yielding in such analyses is basic and not necessarily appropriate as a basis for the design of tall buildings. The design teams therefore applied global NLRHAs, to assess these effects directly across all four projects.

In order to accurately estimate the true seismic demands, extensive non-linear soil structure interaction analyses were performed for a number of these projects. These analyses took account of the neighboring structures and soil conditions to reduce the design demand on the building from standard approaches Figure 6. This in turn has produced substantial savings in material above ground.

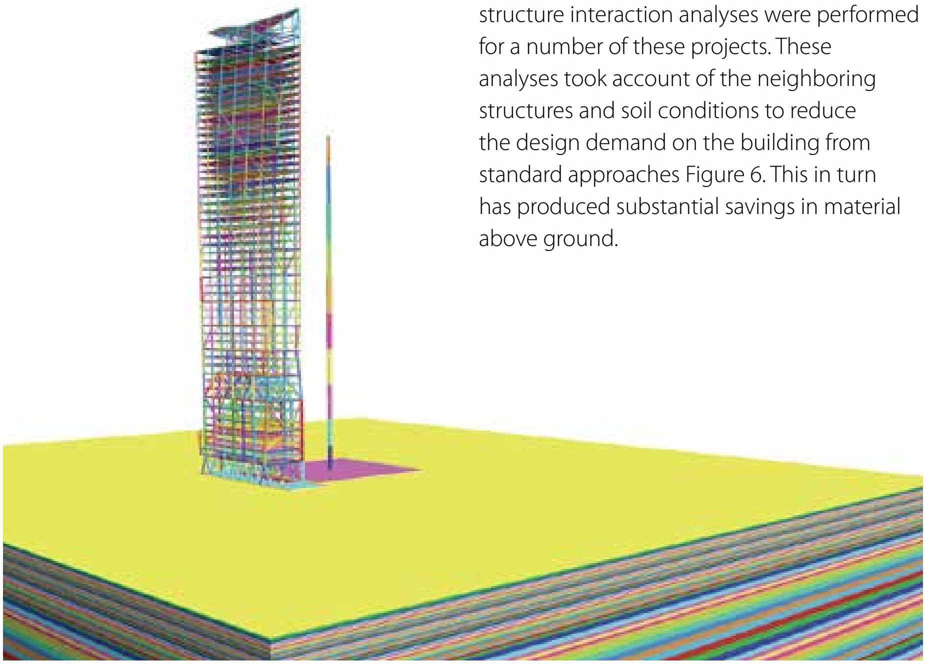

Figure 6. The soil structure interaction model used for Reforma 509 including the neighbouring Torre Mayor. This advance approached helped reduce structural materials in the development. (Source: Arup)

As detailed later, the advanced analytical approached adopted for these towers has provided an enhanced understanding of their likely performance and economy of design.

The Importance of Details

During design, buildings are represented in plans, elevations, and sections. These simplified views enable design but only partially represent reality. Once complete, visitors to a tower may have two impressions; the first as a monumental view of the whole form and the second as a much closer perspective, where they come face-to-face with the sheer scale of the building. The inter-relationship between these scales is fundamental, but may not easily be understood. The impact of a single detail on the global functionality of a building can be profound but hidden. In this section we seek to shed light on some of the key elements which enabled the form and function of these four towers.

1. The Seismic Fuse

Central to the seismic design strategy of BBVA Bancomer is an Eccentrically Braced Megaframe (EBMF), which provides stiffness, strength and ductility. The EBMF provides the tower's lateral stability, resisting design wind and moderate earthquakes elastically. Energy from larger earthquakes is dissipated through the yielding of "seismic links," with the remainder of the frame remaining essentially elastic. This creates a clear and explicit location for yielding under severe seismic response and protects the rest of the structure. The link is analogous to a fuse in an electric circuit; a sacrificial element that protects the rest of the system.

In addition to global assessment, the exceptional scale of the EBMF warranted detailed performance-based evaluation of the plastic fatigue behavior of the ductile link elements. Highly refined sub-models were used to evaluate the plastic fatigue performance of the inelastic elements under the cumulative strain demands due to the MCE earthquake records. Figure 7 shows one of the analysis model employed for the study.

2. Buckling Brace Restraint

Being exceptionally slender, Reforma 509 required a structural solution with maximum inherent stiffness. The perimeter brace system maximizes material that contributes to overturning resistance. Concentric braces provide a direct and stiff axial load path, and can offer the required ductility to dissipate energy efficiently in extreme earthquakes.

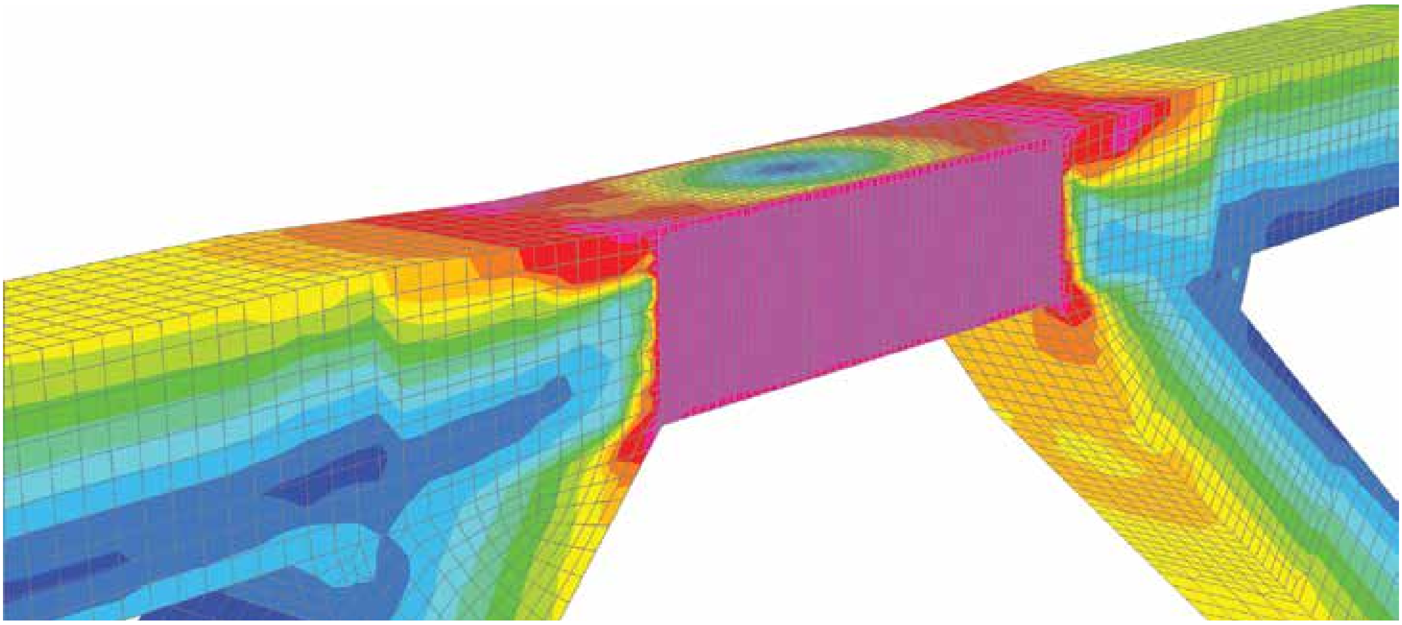

Figure 7. A detailed non-linear analysis mode for the BBVA seismic link – like an electrical fuse these sacrificial elements protect the rest of the system from damage during an earthquake. The contours demonstrate the concentration of plastic strain within the link webs. (Source: Arup)

However, with a column grid of around 9 meters, a single story brace approach would be too shallow and therefore inefficient on typical floor-to-floor heights of 4.3 meters. By introducing a single brace spanning multiple levels with intermediate restraints, an effective bracing arrangement was achieved. With an increase in efficiency, this has the added effect of minimizing the member sizes and opening up as much of the façade as possible to the view of Chapultepec Park, one of the unique selling points of the useable space within the building.

In order to provide sufficient ductility, the structure has been designed as a Special Concentric Braced Frame (SCBF), allowing the braces to undergo controlled plasticity during a large seismic event. To ensure that this ductility is provided over multiple story braces, Arup has developed the bespoke 3-story brace system with unique connection details to allow the braces to rotate while maintaining lateral restraint. (Algaard et al. 2015) This means that the braces are effectively stockier, exhibiting a more symmetrical response than typical for SCBFs, in turn enhancing efficiency. Figure 8 shows the idealized buckling response of the 3-story brace.

The bespoke brace configuration was not directly supported by design codes or physical test programs. Arup therefore investigated the behavior through detailed nonlinear Finite Element simulations, which in turn were verified through comparisons with published test data for standard configurations. The approach was approved by peer review in 2015.

Without the innovation and design of the multiple story braces, the scheme would not provide the same structural efficiency, putting the commercial viability at risk. As such, the bespoke 3-story brace system is

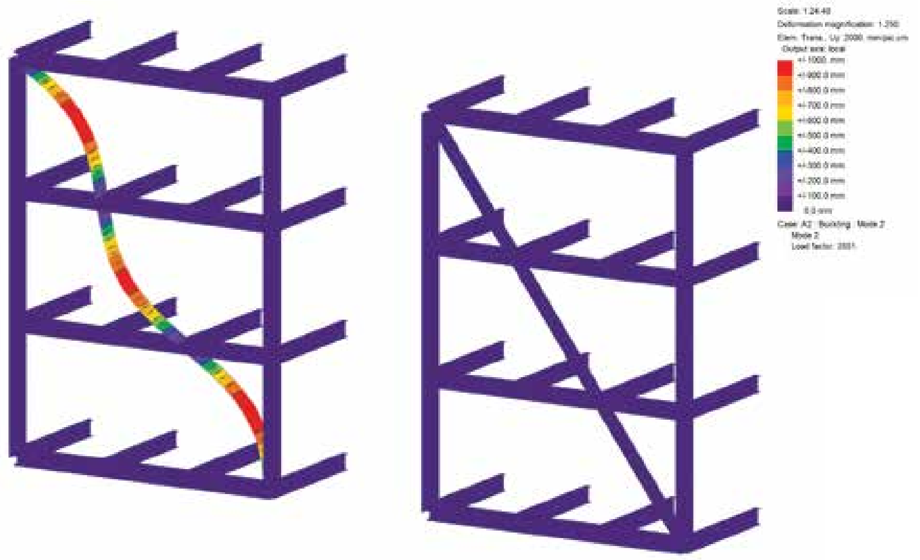

Figure 8. Idealized buckling response of 3-story brace on Reforma 509 (Source: Arup)

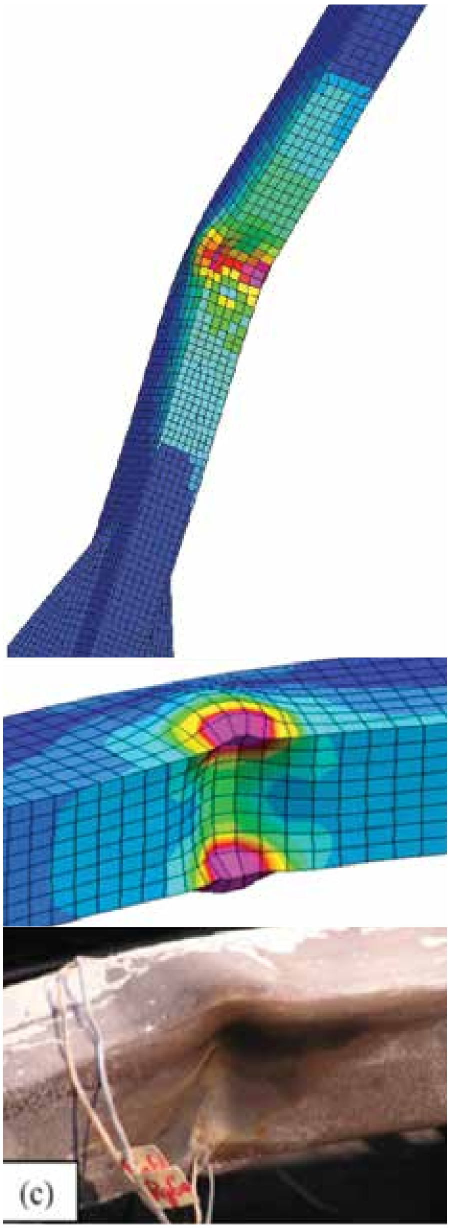

Figure 9. Nonlinear simulation of hinge formation and plastic strain development on 3-story brace on Reforma 509. Test photo from Fell (2008). (Source: Arup)

one of the key components ensuring the feasibility of the project.

3. Balanced V-brace

On Torre Pedregal one of the key efficiency drivers was the balance of the 75m cantilever. By hanging the floors from the V-brace, the backspan balances the cantilever about the base pivot point and substantially reduces the lateral demands in the core under gravity load. It further decouples the V-brace from the lateral system, protecting the gravity system from seismic demands, thus avoiding the need for special detailing of this, as the system remains essentially elastic under the MCE event. The hanging columns provide an additional benefit of column-free lobbies on the east and west faces of the building, Figure 10.

4. The Double V

The double V-bracing along the glazed hypotenuse of the Torre Reforma occurs along a fold in the façade line. As a result the gusset plate at the convergence of the braces, elements from two different planes are captured. To accommodate the element orientations, the gusset is folded to align with the façade surface and sculpted with four fingers slotting through the V-braces Figure 11. This gusset detail occurs every four floors similar to the openings in the concrete shear walls, and reinforces the 4 story rhythm of the structural system. The architect has chosen to express this detail, while minimizing the connections to the concrete shear walls at the opposite end of the brace.

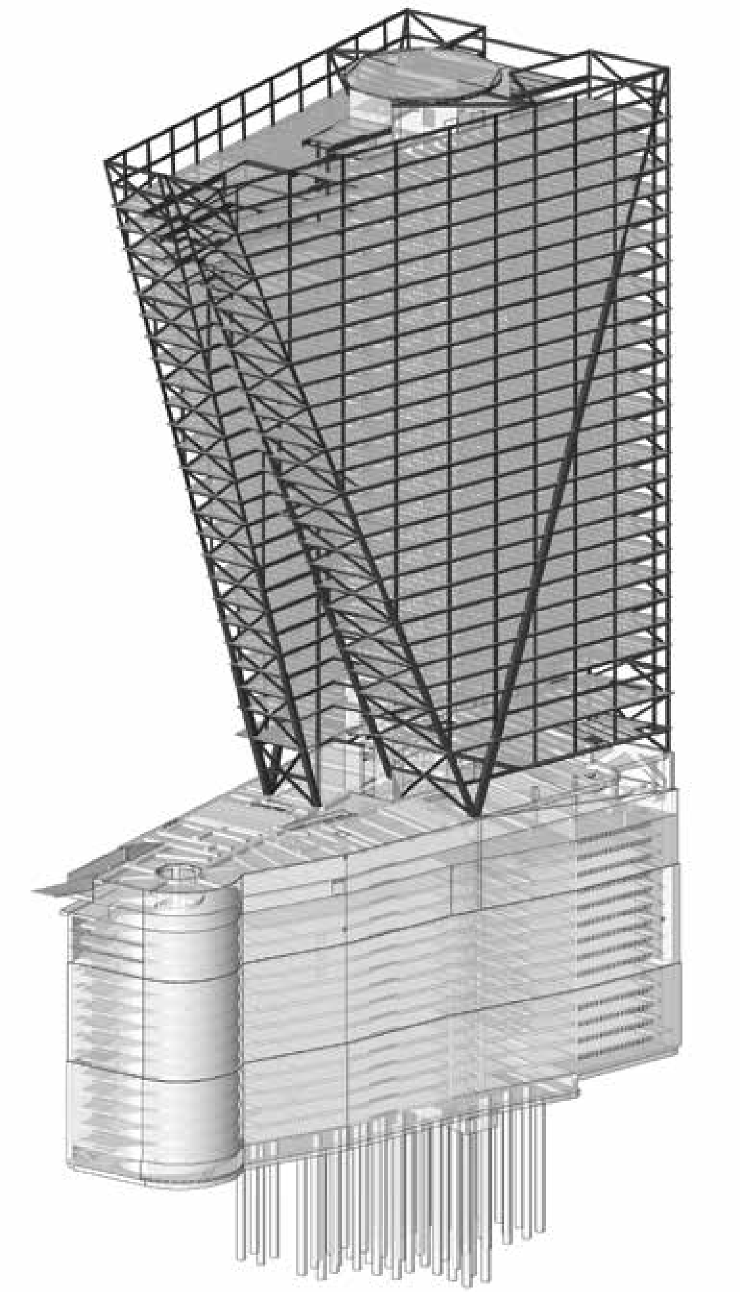

Figure 10. Structural model illustrating the V brace arrangement on 24 Pedregal (2008). (Source: Arup)

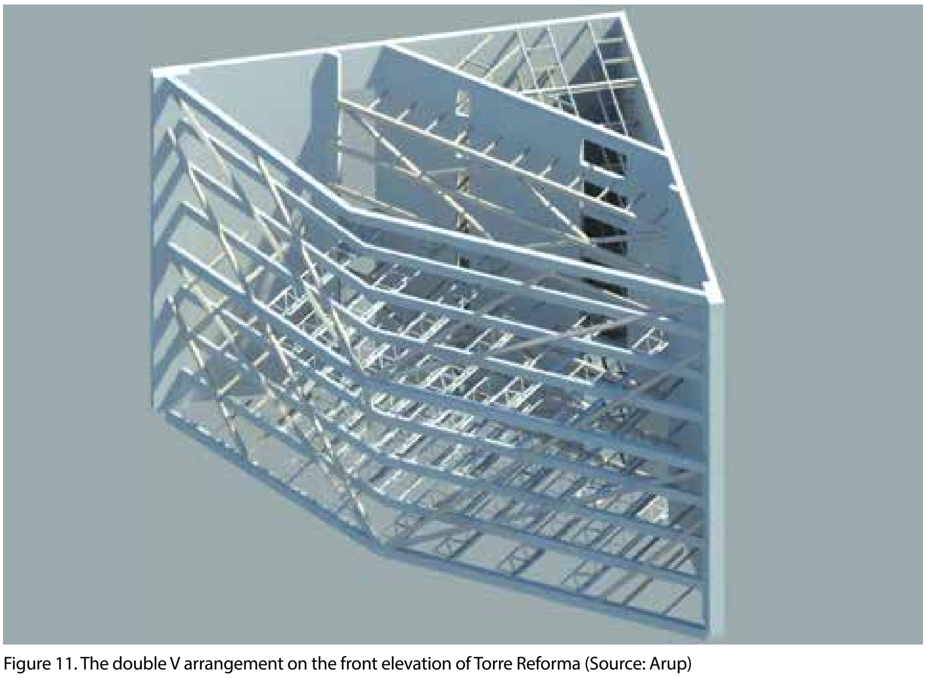

Figure 11. The double V arrangement on the front elevation of Torre Reforma (Source: Arup)

Conclusion

Although the success of these projects cannot be reduced to numerical values, each one has responded to very constrained conditions while maintaining a focus on efficiency. An example of this efficiency-focus is shown below for each of the four projects.

Torre Reforma

$10 Million

Initial foundation studies, based upon the available site investigation data provided by the local engineering team, required the introduction of 181 one-meter diameter drilled caissons to supplement the settlement resistance provided by the diaphragm panels.

Under the direction of Arup's geotechnical engineers, additional site investigation was conducted to enhance the understanding of soil stiffness parameters including pressure meter testing and suspension log shear wave velocity testing. This additional test data, combined with detailed settlement analysis in PLAXIS3D, including staged loading, provided the confidence to eliminate all 181 piles from the foundation system, saving the client an estimated $10Million.

24 Pedregal

100 kg/m² steel savings

The implementation of the V-brace system substantially reduces cost of cantilevering to avoid the historic house located at the foot of the tower. In addition to a reduced tonnage in comparison to a diagrid and moment frame scheme, the system reduces the number of site welded connections allowing for faster erection times. The total structural steel tonnage of the building was over 100kg/m2 less than the moment frame concept scheme in place when Arup joined the project.

BBVA

33 Percent Reduction in Seismic Forces

The Mexico City code does not include specific requirements or guidance for Eccentrically Braced Frames (EBFs). As an alternative source, the American Institute of Steel Construction (AISC 341-05) was adopted as a basis for the design of the EBF system. AISC 341-05's capacity design approach for columns in EBFs is reasonable in low-rise buildings but would be highly conservative for the 52-story Torre BBVA Bancomer which exhibited substantially higher mode seismic response.

Arup's team presented an approach where the column forces are based on non-linear analysis, which gives a representative interaction between the dynamic modes of the building. This approach enabled the authors to reduce column design forces by over 33 percent, saving more than 1000T of steel in the superstructure as well as reducing material use, space take, and complexity in the basement and foundation structure. The approach is estimated to have saved the client $6-8Million. The latest version of the code (AISC 341-10) now explicitly allows this approach.

Reforma 509

50kg/m2 Steel Savings

The primary structure of Reforma 509 has been optimized through the use of a bespoke iterative computational program that refines sizes for all primary members of the building. An extensive study was undertaken to understand the balance between the concrete and steel dimensions of the composite columns, with the result of achieving a steel weight 50kg/m2 lighter than the client's original target. In addition, this high level of optimization has allowed for a reduction in column concrete dimensions such that an extra 350m2 of lettable floor space was created.

Further work undertaken by Smith et al. (2015) has shown that it is possible to improve on this steel saving through the use of higher-strength steel. HE shows that should it be possible to tender and procure Grade 70 steel for the columns and hangers, then an average of 22% tonnage saving could be realized in those elements.

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