# Airport features a Seismic Retrofit during Construction

**By Emmanuel E. Velivasakis and John Abruzzo**

In the early morning hours of August 17, 1999, a tremendous earthquake with a magnitude of 7.4 on the Richter scale struck northern Turkey. Many buildings in and around Istanbul sustained damage from the temblor, even though the epicenter was about 100 km east of Istanbul near the port city of Ismit. The passenger terminal building of Ataturk International Airport, which was under construction when the earthquake struck, also experienced some localized structural distress. In September 1999, the joint venture of Tepe Akfen Vie (TAV), the local build-operate-transfer consortium, and Turner Steiner International, SA, the company that provided construction management services to TAV, decided to hire a technical team to evaluate the seismic resistance of the existing facility and to provide recommendations for improving the performance of the structure, so that the terminal would remain operational after an extreme seismic event.

Following the aftermath of the August earthquake, and in order to perform the seismic evaluation of the above-referenced terminal building, two consulting engineering firms were retained by the design-build-operate joint venture TVA: namely LZA Technology of New York, NY, USA and TUNCEL Engineering of Istanbul, Turkey. In addition, LZA Technology retained the services of two experts in the field of seismic modernization and seismic base isolation: Professor Michael Constantinou and Dr. Andrew Whittaker, both of whom worked closely with the LZA/TUNCEL technical team and assisted with the structural evaluation and subsequent seismic modernization. Professor Constantinou is the Chairman of the Civil Engineering Department at the State University of New York at Buffalo, NY, and Dr. Whittaker is the Associate Director of the Earthquake Engineering Research Laboratory at the University of California at Berkeley, CA.

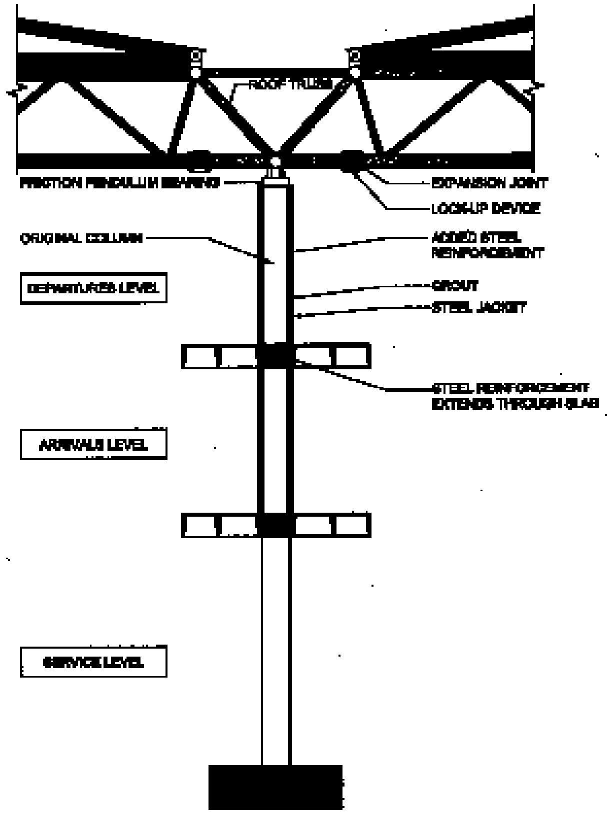
The International Terminal of Ataturk Airport is a huge structure, with three levels and a footprint that is 240 m by 168 m. The first floor of the terminal is the service level; the second floor is the arrivals level; and the third floor is the departures level. The first floor is a cast slab-on-grade. The second and third levels of the structure are elevated slabs on a 12 m grid and are constructed of cast-in-place reinforced concrete. However, on the upper-most level, concrete columns extend to the roof on a 24 m grid. The roof consists of 24 m by 24 m bays and is framed utilizing triangular-shaped, welded and bolted tubular steel space-trusses that extend as a frame along the column lines. This framing supports a two-way vaulted queen-post infil structure forming rectangular pods at each of the bays that support the glass and metal roof of the building. The lateral load resisting system of the building consists of ductile moment frames, as well as a few shear walls. The building is seismically segmented in 48 m by 48 m square pods separated with 50 mm seismic joints. The roof framing has numerous expansion joints to accommodate thermal movements; however, these do not generally coincide with the seismic joints of the structure below. This seismic jointing has resulted in the splitting of the building columns that are located along the expansion joints in halves and quarters. In addition to these typical pods, one pod was partially framed with a penthouse slab to house light mechanical equipment at the roof level.

When the technical team conducted a field inspection and evaluation of the structure it observed structural damage and evidence of structural movement. The team found four areas of structural distress that were particularly pressing.

It was noted that the tops of several of the columns at the departures level appeared to have suffered localized damage. The roof steel space-frame was supported on top of the concrete columns with anchored base plates. Damage at these locations occurred either by the shearing of the anchor rods or the bursting of the surrounding concrete, allowing the steel frame to free itself from the concrete support.

Another type of structural distress was observed at the cantilever columns, which extend to the roof level. The columns that exhibited failure of the roof connection due to excessive lateral load experienced a considerable reduction of lateral load after failure. As the connection failed, the load carrying capacity was reduced. This reduction in capacity resulted in a redistribution of the roof shear. The consequence was that those columns with intact connections absorbed a greater load. When the lateral load at the top of the column became excessive, the concrete cover spalled and large flexural cracks appeared at the departures level. Again, the variation in strength of the typical connection was a consequence of the unfinished construction.

Another type of structural distress that was visible on all three levels concerned flexural cracking of miscellaneous structural components. Examples of this were slabs in the vicinity of shear walls and beams at the column connections. Lastly, several of the exterior glass curtain-wall panels suffered breakage and/or cracking because they were not yet completed at the time of the earthquake.

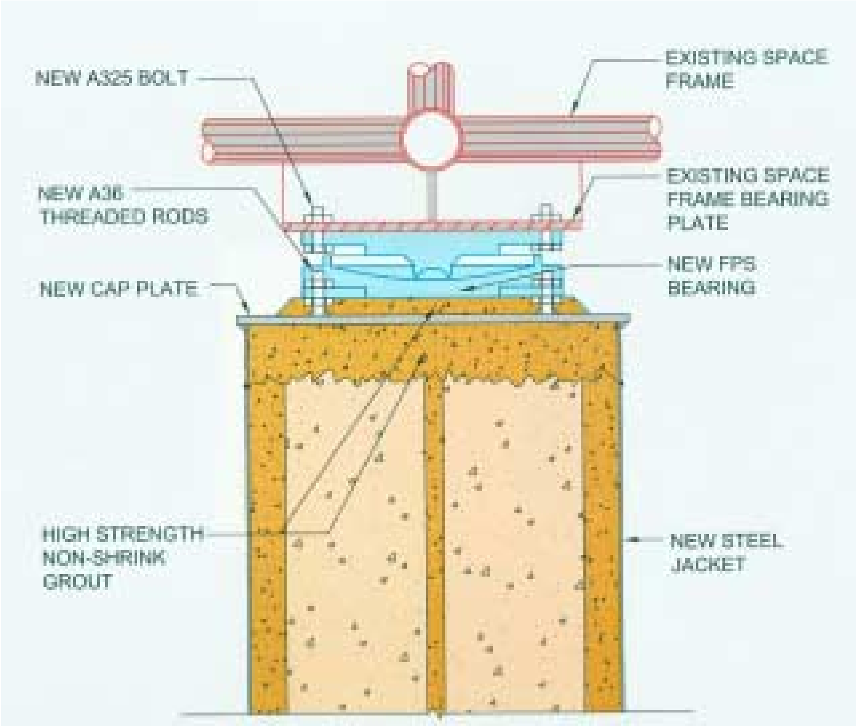



*Terminal Building construction showing steel reinforcement.*

It was clear that the engineers who designed the terminal considered seismic loads and heeded the requirements of the Turkish building code in order to enhance the seismic performance of the entire structure. The structural drawings indicated that the building had been divided into many segments by utilizing directional seismic expansion joints. The foundations of the individual column footings were tied together with strap beams. The beams and columns were generally sized so that plastic hinges would form in the beams not the columns (the strong column condition).

Based on the team's site observations and after considerable analysis, it was clear that a large amount of the structural distress was concentrated at the terminal's departures level. Specifically, it was concentrated mainly at the top of the columns where the steel frame is supported and at the base of the columns. In particular, it appears that many of the connections of the space truss to the top of the columns sustained the damage, causing a redistribution of seismic loads to adjacent columns. This load redistribution traveled in unpredictable load paths, causing the inadvertent loading and overloading of components. In addition to this distress, the steel space truss bolted connections at the expansion joints were affected by the unintentional distribution of the loads. It was the opinion of the technical team that these bolted joints needed specific attention during the seismic upgrade of the building. The technical team concluded that the primary reason for the observed damage was due to the "incomplete state" of certain key elements of the structure, including some of the support connections of the space frame roof to the reinforced structure below.

Since the facility was scheduled to open in January 2000, any structural




*Top left: Retrofitted column with seismic isolator.*

*Bottom left: Typical lock-up device (Courtesy of Taylor Devices, Inc.)*

modifications were limited by both time and accessibility constraints. Therefore, the seismic upgrades had to be completed as quickly and efficiently as possible to meet this extremely tight deadline. Since most of the computer equipment, baggage handling equipment and HVAC equipment had already been installed, access to the lower levels of the terminal was virtually impossible.

Base isolation would have been an optimal solution; however, given the stringent time restrictions and a lack of accessibility, a foundation retrofit would have been impossible. The technical team decided that the best course of action would be to isolate the space frame roof seismically from the rest of the building. This type of remediation would relieve both the steel frame roof structure and the departures-level columns from resisting high seismic loads in the future. However, this kind of seismic isolation required that additional measures be taken in order to ensure that the isolation would behave in a consistent manner with the balance of the building structure.

Isolation was achieved with the installation of Seismic Isolation Devices (SID's) under the steel space frame supports, at the top of the departures-level columns. The team decided to use friction-pendulum type isolators because they are compact, non-directional, and can readily accommodate the large deformations expected. These isolators would allow the roof to swing like a pendulum, from side to side, as much as 250 mm during an earthquake. The roof shear is controlled by the friction coefficient of the isolators, thus allowing a reduction of the shear to acceptable levels in the columns below. The movement of the steel roof would be inconsistent with the movement of the penthouse slab. Therefore, rather than installing the required expansion joints and upgrading the penthouse slab support structure, it too was retrofitted to float with the roof. In all, 130 friction-pendulum-type isolators, manufactured by Earthquake Protection Systems, Inc. of Richmond, California, were installed in the terminal.

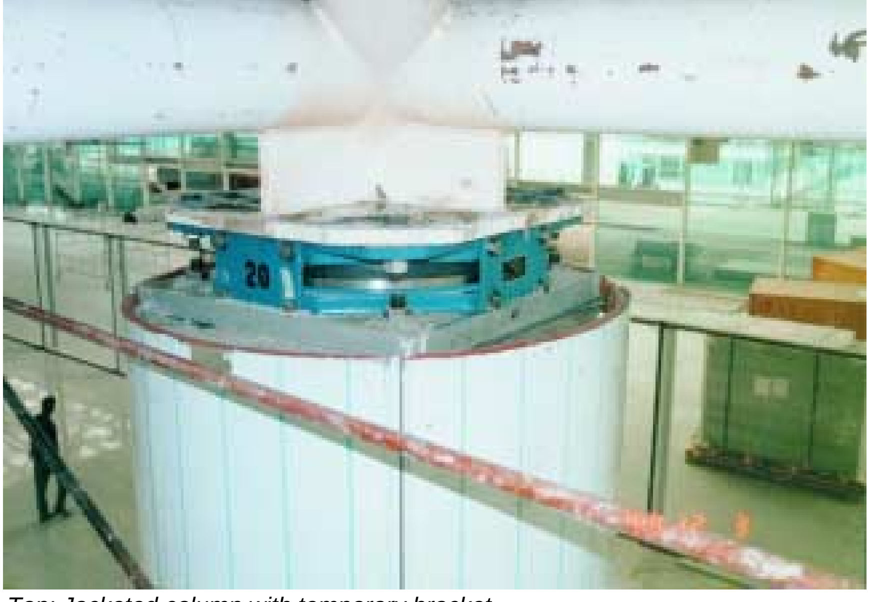
Since time was a major factor, the devices selected were essentially stock items. Therefore, the team could not select or specify a conservative design displacement. Rather, we were limited to a displacement capacity of 250 mm. This displacement capacity was uncomfortably close to the deformation demand computed by elastic analysis. To ensure that the SID selected was appropriate, a non-linear dynamic analysis was performed, using a model structure. The degradation of the lateral system was determined with a push-over analysis, and the plastic hinge behavior was developed utilizing in-house software. The analysis was performed with IDARC2D (courtesy of the National Center for Earthquake Engineering Research) and also with SAP 2000 Non-Linear (developed by Computers and Structures Inc.)

As a result of using the SID's, the team also recommended that every building element that connected to the steel framed roof or penthouse be retrofitted to accommodate the potential movements of the roof during a seismic event, without subjecting these elements to excessive stress.

The second step in the seismic upgrade process required the installation of steel jackets on the 88 columns that extend to the roof at the upper two levels. The jacket served two purposes. In general, a jacket provides a tremendous increase in ductility and shear strength. In addition, the column previously split by the seismic expansion could be rejoined to effectively create a single column. The columns would then behave in an integral fashion to increase the column strength and stiffness, as well as providing support for the SID's. All voids within the jacket were filled with a non-shrink, high-strength grout, from the departures level all the way down to the arrivals level.

Once the jacketing of the steel columns on the top two levels was proposed, it was also necessary to eliminate the existing seismic expansion joints located on the 48 m module at these levels. This elimination of the seismic joints, along with the jacketing of the columns, is extremely beneficial to the overall seismic performance of the building. The technical team proposed an elimination of the expansion joints by removing the existing Styrofoam filler from within the joints, filling the void with grout, and providing a steel connection between pods to transmit diaphragm forces.

One last item of importance was to ensure that the expansion joints within the steel truss roof frame still had the ability to accommodate thermal movement. These joints had to be eliminated for seismic-induced movement, yet could not be eliminated for temperature-induced movement without tremendous modification. Therefore, the final step in the seismic upgrade required that the thermal expansion joints in the roof



*Top: Jacketed column with temporary bracket..*

*Above: Isolator in a finished state.*

be outfitted with a set of Lock-Up Devices (LUD's), located at key roof space-frame expansion joints. The LUD is designed to allow movement through the device when the motion occurs at a slow rate. However, the device will lock when the movement occurs quickly, as would be expected during a seismic event. This device effectively allows the space truss framing to move for thermal loads, but creates a diaphragm during a seismic event. This provides a rigid roof structure and allows the space truss framing to act as a single structural unit. The LUD's selected were manufactured by Taylor Devices, Inc.

Construction moved forward at a rapid pace. The process started with the jacketing of the columns. Then a bracket was connected to the jacket to support the jacks. The jacks were installed and the steel truss was lifted off the column top; then the column top was removed. The joint extension was then installed and the column top was grouted. At this point, the SID was inserted and connected to the top of the column cap and the roof frame. Finally, the jacks were removed and the column closure was installed. The Ataturk International Airport terminal opened on time in January of this year amid much fanfare. The swift seismic modernization of the $305 million terminal now ensures that the building will continue to function after a "design-magnitude" earthquake in the future. Due to these last-minute seismic upgrades, the newly retrofitted terminal will now be able to remain operational during an extreme seismic event. The use of seismic isolators at the roof level is a "groundbreaking" achievement for all of the engineers involved in this seismic upgrade. These exciting techniques will pave the way for future developments in engineering technology.

*Emmanuel E. Velivasakis is Senior Vice President and Principal with LZA Technology, a Division of the Thornton-Tomasetti Group Inc. (email: evelivasakis@lzatechnology.com). John Abruzzo is an Associate with LZA Technology, a Division of the Thornton-Tomasetti Group Inc. (email abruzzo@lzatechnology.com).*