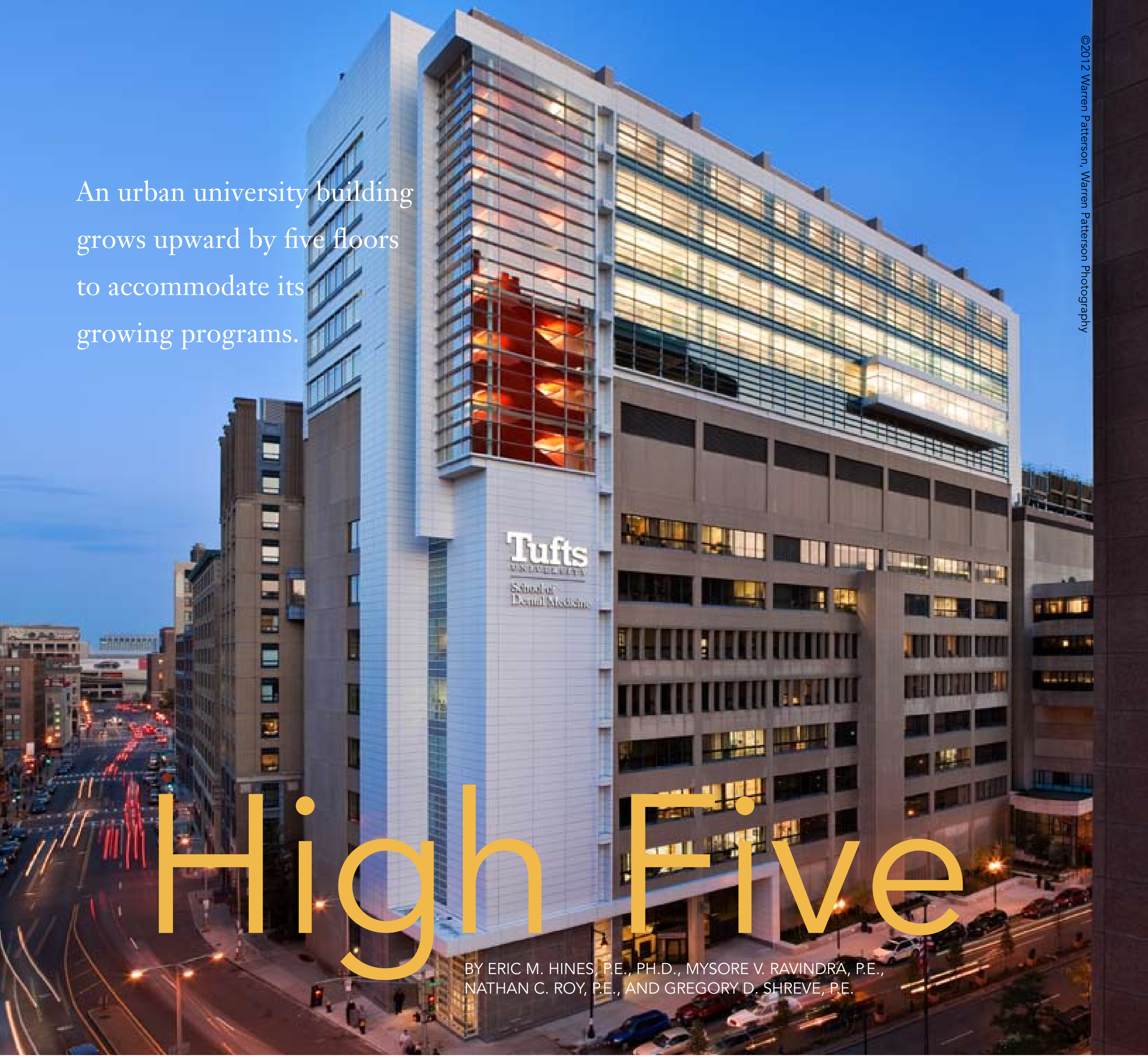

High Five

An urban university building grows upward by five floors to accommodate its growing programs.

BY ERIC M. HINES, P.E., PH.D., MYSORE V. RAVINDRA, P.E., NATHAN C. ROY, P.E., AND GREGORY D. SHREVE, P.E.

SOMETIMES, THE ONLY WAY to go is up.

This is especially the case for facilities in dense, urban areas that find they need more space.

The Tufts University School of Dental Medicine in downtown Boston recently added two new clinical patient floors, an enlarged simulation lab and teaching facilities for students, as well as a continuing education conference center and administrative offices. And it did it by expanding upward, adding 105,000 sq. ft in five stories on top of its existing 10-story structure built in 1972.

The need for more space presented a compelling architectural challenge to integrate a prominent new steel-framed addition with the original building's aging precast concrete exterior—and one that would allow the existing teaching and clinical spaces to remain in use during all phases of the project. Tufts turned to architect ARC/Architectural Resources Cambridge to develop a new exterior vision for the building and the school. The expansion created a distinctive new image for the school, which marks the gateway to the Tufts Health Science Campus.

The new design successfully integrates the old and the new by extending the new façade down the prominent northwest corner of the building to the ground-level entry, fusing the new design with the existing building. A horizontal "bump-out" cantilevers 8 ft from the building's west face to compliment the vertical expansion of the existing building. The updated vestibule, entrance canopy and stone façade add to the new image of the building, creating a positive first impression for visitors and students. Structural framing and precast panels at the northwest stair were removed two stories down to the ninth floor and replaced with a seven-story glass-enclosed orange metal-clad stair with exposed round HSS 12.75-in. framing. Visible from street level at night, the stairwell serves as a focal point for the building. The existing precast panels at the northwest corner were clad with metal panels to connect the new expansion with updates at the street level.

The five-story expansion contains floor-to-ceiling windows, allowing natural light to penetrate deep inside the 92-ft-wide by 245-ft-long structure, and provides sprawling views of Boston. The incorporation of two internal stairwells in the expanded section, between the 12th and 13th floors and the 14th and 15th floors, allows users to easily flow from one floor to the next and promotes collaboration and interaction between the educational and clinical floors.

A Matter of Load

The existing 10-story, 180,000-sq.-ft building was designed by The Architects' Collaborative (TAC) for a site that is now


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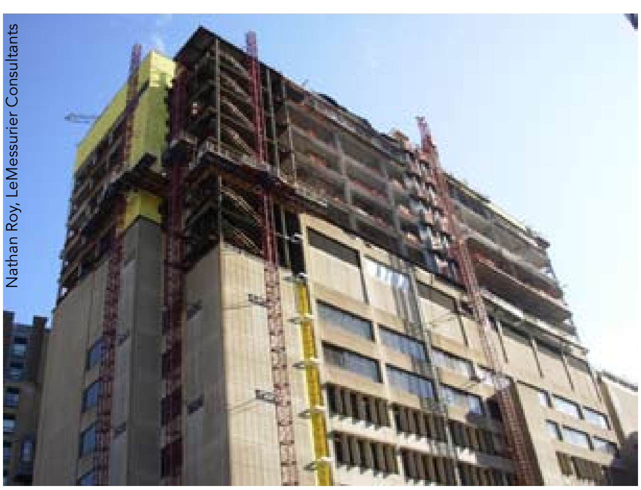
▲ A new column at an existing offset column splice.

► The northwest stair of the building is a key architectural component of the expanded structure.

▼ The expansion added five steel-framed stories onto an existing 10-story building.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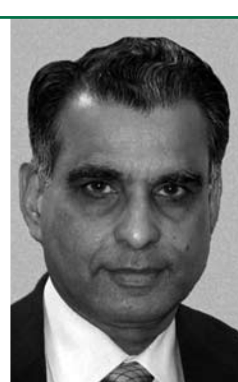


Erection of the steel framing.

Construction of the original foundation.

bounded by two buildings, two busy streets and a subway tunnel. Although the original building had been engineered to accommodate future levels, substantial changes in wind and seismic loads complicated the question of how many stories could be added to the structure without disturbing building operations.

Tufts University approached LeMessurier Consultants to ask whether a vertical expansion of the building would be possible, as they had received a report by prior consultants stating that expansion would not be feasible due to significant changes in the building codes and a lack of detailed information on the pile foundations supporting the building. LeMessurier encouraged the University to reconsider this conclusion in light of a more detailed study that included sophisticated conceptual and computational models and an in-situ exploration of existing conditions to determine the precise level of upgrade required for existing members and details. In the end, five stories was deemed the optimal expansion size in order to minimize the required structural strengthening of the existing structure.

The structure was originally designed with braced frames in the short direction and moment frames in the long direction to resist 20-psf uniform wind load. The original building was 154 ft high, and the original base shear due to wind was 733 kips in the short direction. As originally conceived, the addition of five new 14-ft-high stories, plus a 20-ft wind screen, would increase the height to 244 ft, resulting in a total wind load of 1,160 kips in the short direction. The governing code (Massachusetts State Building Code, 6th Edition) for the expansion required wind loads that exceeded the original code loads by 23%. Detailed elastic modeling of the expanded structure demonstrated that this difference could be accommodated with an allowable stress increase of one-third in the members and connections. Results were similar for the moment frames in the long direction.

While wind controlled the design of braces and their connections, seismic forces governed the column splices under overturning forces. The code required amplification of the column splice forces by $0.8R$ for this equivalent OCBF ($R = 5$) structure, resulting in an amplification factor of 4. Under this restriction, column splice forces calculated according to equivalent lateral force procedures would have required reinforcing of nearly every column splice in the braced frames, and rendered the project infeasible due to the requirements for operational continuity of the building. Furthermore, any attempt to bring the original brace members and connections into conformance with OCBF requirements also would have prevented the project from moving ahead.

Upon considering options for more advanced linear and non-linear dynamic procedures to evaluate the lateral system, an initial study was conceived to evaluate the extent to which non-linearity was expected to play a role under a site specific analysis. For this purpose, the designers applied methods similar to those described by Hines et al (see "Ground Motion Suite Selection for Eastern North America" in the March 2011 edition of ASCE *Journal of Structural Engineering*) to select a large and richly varying suite of over 60 relevant ground motions. Modal analyses based on these ground motions, amplified according to the site, showed elastic behavior under all ground motions in the short direction and panel zone yielding under only two ground motions in the long direction. Furthermore, initial assessments of the seismic story shears compared with story shears from wind loads implied that the effective *R*-factor of the braced frame was approximately 2 instead of 5. The effective *R*-factor is defined at the *R*-factor divided by the ratio of wind story shear to seismic story shear (buildings that are governed by wind loads have lower effective *R*-factors).

Based on this initial screening, it was determined that non-linear analyses would only add to the building assessment if they were used to construct performance limits based on incremental dynamic analyses. Since the object of the initial assessment was to demonstrate feasibility of the vertical expansion in conformance with the governing code, and since the chances of elastic response to a 2% in 50-year event appeared quite high, further work was restricted to detailed modal analysis of the structure to determine the precise level of column splice reinforcement required by code. A linear dynamic approach to the problem allowed designers to take advantage of the fact that higher mode effects decreased the overturning forces on the column splices. This work resulted in identification of four locations in each frame on the first and second floors of the building where existing column splices would require reinforcement.

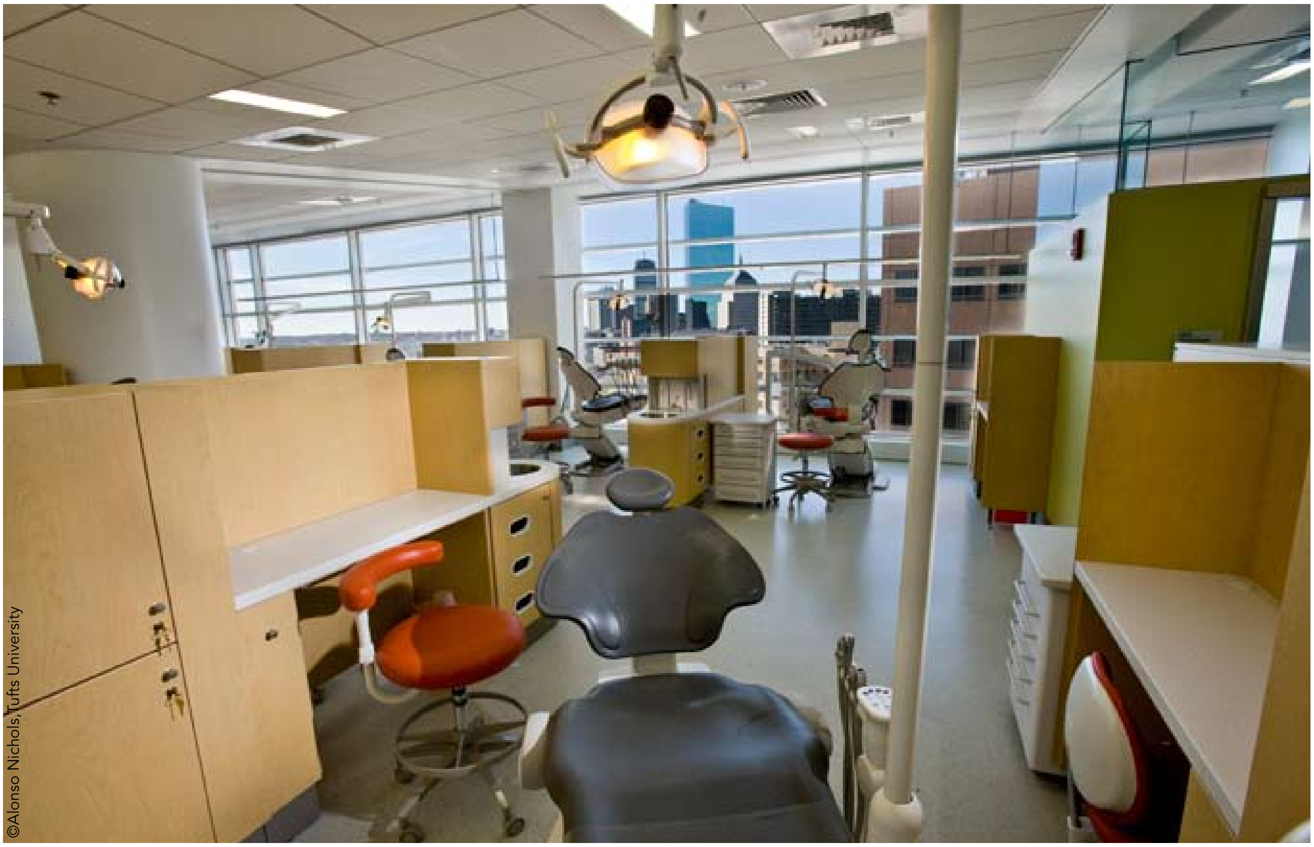
While reinforcement requirements for the steel frame could be minimized based on close scrutiny of existing documents, detailed analytical studies and in-situ investigations of the existing connections, missing pile layouts and details prevented answers to questions regarding the ability of the foundations to resist uplift forces due to overturning forces under wind loads. In order to address this challenge, LeMessurier developed an investigation program that began with scanning all basement pile caps to determine the number of piles and their locations for each group. While the scans combined with the original column schedule and foundation layouts were able to support assessments of the pile groups under compression, missing splice details between the piles and the pile caps prevented detailed assessment of the lateral system's tensile capacity at the foundations. This uncertainty and its implications were thoroughly discussed with Tufts, ARC and the peer review engineer, which resulted in a decision to specify in the construction documents the necessary tie-down reinforcement required should investigative demolition reveals insufficient pile-to-pile cap connection.

During construction, the investigative demolition revealed adequate splices between the piles and the pile caps, and resulted in removal of the tie-down requirements at a benefit of approximately $1 million to the $68 million dollar project. This investigative demolition consisted of excavating next to selected pile caps, exposing a single pile and chipping into the pile caps to find the splice reinforcement. Piles were assessed by the project's geotechnical engineer, McPhail Associates, to have a tension capacity of 25 tons per pile, nearly twice the demand of 26 kips per pile. Selected #8 splice bars were chipped free over their entire length in the 6-ft, 6-in.-deep pile caps. These bars were assessed to yield at 47 kips, over seven times the demand of 6.6 kips per bar. In order to assess their development into the pile, individual bars were pull-tested to 19.7 kip/bar proof loads, which demonstrated a minimum safety factor of 3. Pile caps were repaired with steel friction reinforcement, epoxy grouted to the original pile cap to fully develop the pile strength.

Up from the Top

In addition to the investigation and analysis required to verify the lateral system and minimize its reinforcement, several other measures were required to set the new steel frame on top of the existing structure. Existing columns at the roof were surveyed to be out of tolerance by as much as 2 in. While this was an acceptable tolerance for the existing building interior columns, it allowed for no additional tolerance on the new columns above. LeMessurier identified this potential issue early in the design process so that the project was bid in anticipation of required corrective measures. When the final survey results were reported during construction, cap plates for the existing columns were developed to allow new columns to be placed at their ideal grid points. LeMessurier determined the origin points of the ideal grid for the vertical expansion as the result of an optimization study that minimized the reinforcement required to resist eccentric loads on the existing columns.

Detailed analysis of existing full story transfer trusses over an auditorium in the existing structure helped to determine that no additional reinforcement would be required to support the vertical expansion. LeMessurier also advised the contractor, Shawmut Design and Construction, to account for the effects that the flexibility of these trusses would have on the proposed tower crane landing points. Ultimately, this investigation led to the placement of the tower crane in another part of the structure. The height of the new structure, combined with its tight location between existing streets and buildings, presented an erection premium that motivated the designers to reduce the piece count to the greatest extent possible. To this end, most new floors were framed with beams at 15 ft on center, supporting 16-gage deck running continuously for three spans, resulting in a 12% piece count reduction. Floor framing was sized to exceed the vibration performance of the existing building framing. This was not possible on the 14th Floor, which was subject to the vibration requirement of keeping velocities below 2,000 micro-in./sec under a range of walking regimes. This vibration criterion was met by limiting slab spans to 10 ft and increasing the stiffness of floor beams and girders as required. Reducing piece count and mitigating vibrations, along with designing the moment frames in the long direction, three monumental stairs and a perimeter screen wall at roof level, resulted in a total steel weight of 655 tons.



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The expansion, which totals 105,000 sq. ft in five floors, includes clinical patient space an enlarged simulation lab and teaching facilities, conference center and offices.

As mentioned, a key architectural feature of the new structure was the stairway in the building's northwest corner. This stair and its associated glass façade were designed for prominent physical and vertical integration between the new and existing structures. LeMessurier designed and detailed the stair with long spans, no intermediate hangers and high-vibration performance, and designed two other monumental stairs in the expansion for similar criteria. Both the northwest stair and two monumental stairs were designed for a peak acceleration limit due to walking of 0.5% g and a minimum natural frequency of 9 Hertz. Construction of the northwest stair was carefully coordinated so as to leave portions of the existing tenth floor open during construction. Only after the majority of steel framing had been erected was the existing northwest stair framing removed two stories down to the ninth floor, and the new HSS framed stair completed in its original place.

Since its completion in 2009, the project has fulfilled not only the needs of the school and its students, but also the neighboring community. The expanded and improved facility better positions the Dental School to increase enrollment, hire more faculty and deliver on its tradition of community service, benefiting more than 20,000 patients annually. And in an era where natural resources are scarce, it sets a standard for both environmental and urban stewardship. MSC

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