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DESIGN PHILOSOPHY FOR STEEL STRUCTURES IN MODERATE SEISMIC REGIONS

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ABSTRACT

The authors propose a design philosophy for steel buildings in moderate seismic regions that draws on familiar concepts of ductility and capacity design, but also integrates the concepts of reserve capacity, elastic flexibility and strength to broaden the field of design possibilities. The paper discusses structural systems representing each of these concepts: Moderate-Ductility Concentrically-Braced Frame Dual Systems—reserve capacity; Moment Frames—elastic flexibility; and Eccentrically-Braced Frames—ductility and capacity design. The paper discusses the role that strength plays in each of these concepts and its relationship to design for wind loads. In conclusion, the paper outlines the need for future research related to the continued development and validation of this philosophy.

Introduction

Recent widespread adoption of the International Building Code has introduced seismic design to regions of North America that heretofore have not been required to consider earthquake hazard. This sudden impact of seismic design and detailing requirements on moderate seismic regions has revealed a serious concern: the structural engineering community has not developed and articulated a rational seismic design philosophy for moderate seismic regions. As a result, engineers in moderate seismic regions are compelled by law to design structures according to prescriptive requirements that are untested. These untested requirements can lead to designs that are both unsafe and unnecessarily expensive. The current state of seismic design in Eastern North America underscores the need for transformation that hinges on a new, overarching philosophy—a rational design philosophy that is rooted in fundamental understanding of structural response to the types of seismic events and construction practices specific to the East.

The authors propose a philosophy that draws on familiar concepts of ductility and capacity design, but also integrates the concepts of reserve capacity, elastic flexibility and strength to broaden the field of design possibilities. The paper discusses structural systems representing each of these concepts: Moderate-Ductility Concentrically-Braced Frame (CBF)

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Dual Systems, which employ reserve capacity; Moment-Resisting Frames (MRFs), which employ elastic flexibility; and Eccentrically-Braced Frames (EBFs), which employ ductility and capacity design. The paper discusses the role that strength plays in each of these concepts and its relationship to design for wind loads. In conclusion, the paper outlines the need for future research related to the continued development and validation of this philosophy.

Moderate-Ductility Dual Systems and Reserve Capacity

Designers in the East attempting to develop lateral systems that address moderate seismicity both safely and cost-effectively often find themselves constrained by code requirements that do not provide the flexibility that is available in the West. Many buildings are currently designed using a response modification coefficient, R, equal to 3, which allows seismic detailing to be ignored. This approach has not been proven to guarantee acceptable seismic performance. Furthermore, using $R = 3$ can result in design forces in the building and its foundations that are higher than forces resulting from wind loads, thereby increasing cost without clearly achieving elevated performance. In view of these limitations, new design approaches and system configurations may provide designers with opportunities both to ensure better seismic performance and to reduce cost. The authors of this paper are engaged in an ongoing effort to introduce a dual system for Seismic Design Categories A, B and C that allows $R = 5$ when a stiff primary system is combined with a flexible moment frame reserve system to form a moderate ductility dual system. As summarized by Hines et al. (2009), collapse performance of braced frame systems that possess limited ductility appears to be impacted less by a system's strength than by its reserve capacity. Provided that reserve capacity behavior can be clearly understood through ongoing research, it may be justified to design buildings for lower forces than required by $R = 3$. For now, the value of $R = 5$ has been selected to ensure that wind loads control the primary lateral design in most cases, while ensuring basic minimum force requirements in the long directions of buildings that are not square.

Both large-scale experimental evaluation of connection and system behavior, and numerical simulations of system response are necessary to better understand the collapse performance of the prevailing design approach ($R = 3$) and to develop new design approaches ($R = 5$). An ongoing testing program is studying flexural cyclic behavior of beam-column connections with gusset plates for CBFs (Stoakes and Fahnestock 2010). These experimental results will provide new data on inherent reserve capacity within CBFs and will contribute to numerical simulations of both $R = 3$ and $R = 5$ systems.

A moderate-ductility dual system would be designed as follows. Two separate lateral systems are designed, each for $R = 5$. One is a braced frame, which due to its inherent stiffness meets drift criteria. The other is a moment frame designed with no consideration of drift. For the prototype buildings studied by Hines et al. (2009), this approach leads to wind controlled designs for all building heights above three stories. Even for the three-story buildings, the seismic forces are only 27% greater than the wind forces. Design calculations for the reserve MRF show that MRF seismic forces range between 56% and 59% of the CBF seismic forces, and vary between 20% and 75% of the wind design forces depending on the story height. These MRF seismic forces can be resisted by members that resemble gravity framing in depth and weight. The resulting moderate-ductility dual system behavior can be viewed from two different perspectives:

1. A stiff primary braced frame with a moment frame reserve system to prevent collapse in the event of brace failure.
2. A flexible moment frame stiffened by a sacrificial braced frame designed to withstand wind loads and to provide service-level drift control.

Fig. 1 illustrates the context for the moderate-ductility dual system, where it is contrasted with low seismic (wind) design that requires very little system ductility and high seismic design that requires large system ductility. In the case of high seismic design, the system ductility is achieved through large component ductility, e.g., plastic hinges, brace buckling or brace yielding. In contrast, the different stiffnesses of the braced and moment frames in the moderate-ductility dual system provide system ductility without requiring component ductility.

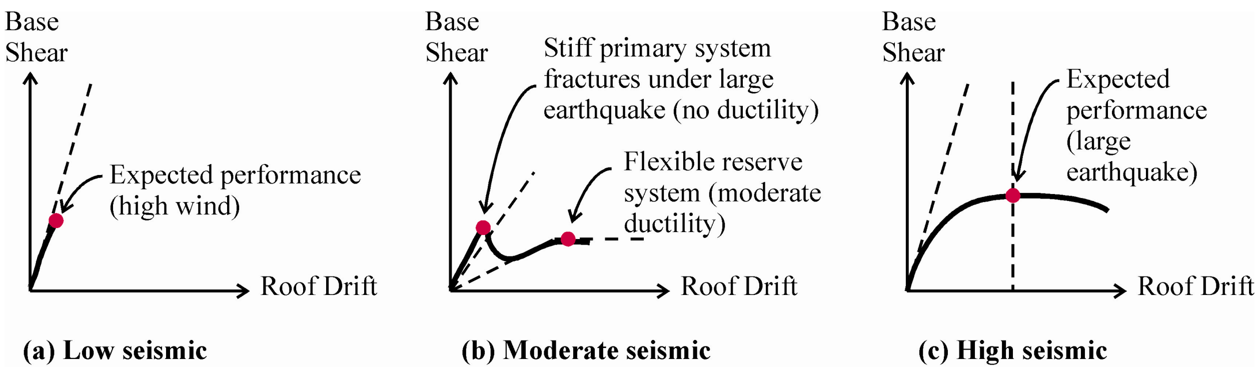

Figure 1. Schematic system behavior for low, moderate and high seismic demands.

Historical Note on Dual Systems

This section highlights past provisions and research demonstrating that the dual system concept has a rich history and may be readily applied to moderate seismic regions with a high degree of confidence. To the authors' knowledge, the earliest formal appearance of the dual system concept was in the original 1959-1960 Structural Engineers Association of California (SEAOC) Blue Book (SEAOC 1960). This concept appeared in the Uniform Building Code (UBC) for the first time in 1961:

> Section 2313 (j) Structural Frame. Buildings more than 13 stories or one hundred and sixty feet (160') in height shall have a complete moment resisting space frame capable of resisting not less than 25 per cent of the required seismic load for the structure as a whole. (UBC 1961, p. 109)

In the 1980s, the U.S.-Japan Cooperative Earthquake Research Program sponsored full-scale pseudo-dynamic prototype tests in Japan and 0.3-scale shaking table tests at Berkeley of a 6-story CBF dual system and a 6-story EBF dual system. These frames were both designed for significantly higher loads than the current U.S. standard because their design represented a compromise between the higher Japanese loads and the lower U.S. loads. Whittaker et al. (1990) provided a clear synopsis of the work and its conclusions. The following excerpt is from this report. For the CBF dual system, the fifth story brace ruptured under maximum shake table excitation and the story was stabilized by the dual-system moment frame:

> The rupture of the concentric braces in the fifth story is clearly evident in Figure 7.2 where the V_{BRACE} component becomes negligible for the MO-65 Test at the point of maximum inter-story drift index (=1.89%). In this story, the DMRSF [dual moment resisting space frame] resisted the total story shear following the rupture of the concentric braces, with only a minor degree of inelastic behavior. (Whittaker et al. 1990, p. 97)

Fig. 2 shows Figure 7.2 from Whittaker et al. (1990). Both the original dual system language in SEAOC and UBC, and the results of this research imply that the moment frame was conceived as and performed as a reserve system, providing a failsafe in the event of degradation in the primary system. The fifth story force-displacement plot in Fig. 2 also shows that the reserve system remained essentially elastic even after the brace fractured.

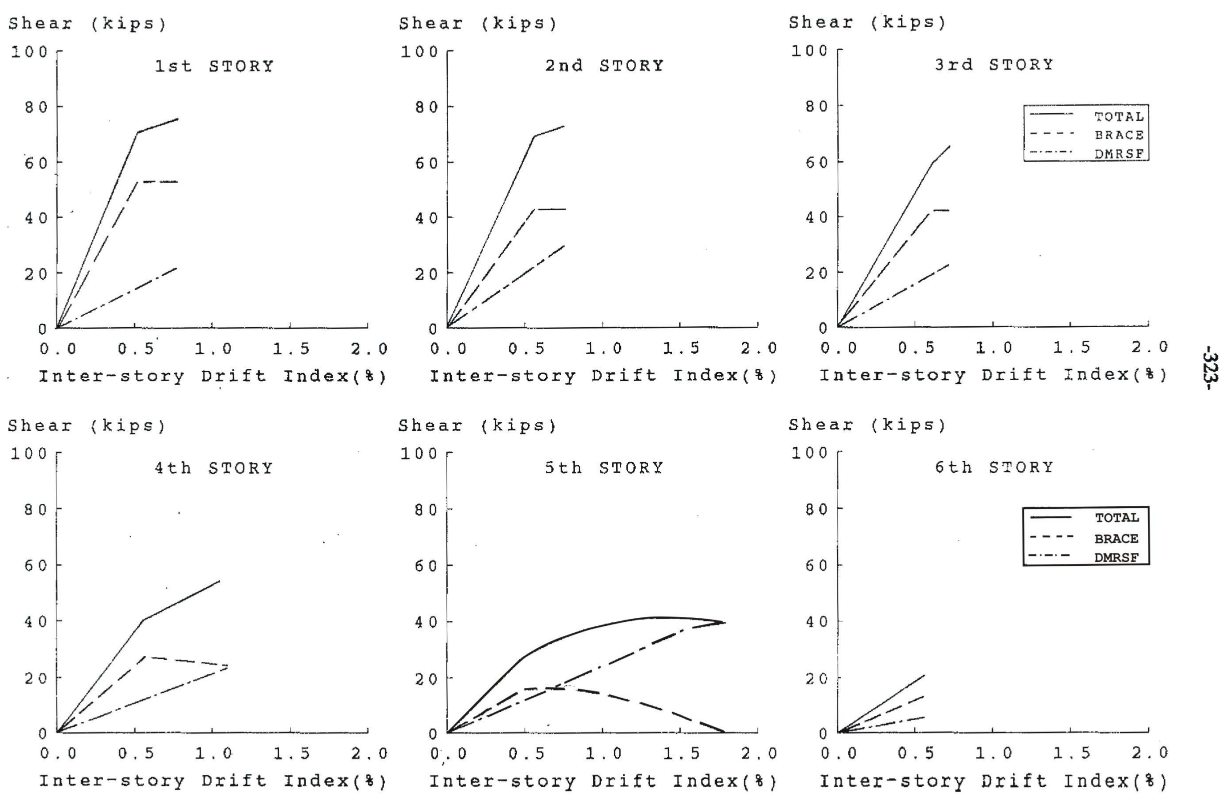

FIGURE 7.2 CBDS STORY SHEAR AND INTER-STORY DRIFT INDEX ENVELOPES

Figure 2. UBC/EERC-88/14 Figure 7.2 showing fifth story shear resisted by moment frame after brace rupture.

By the end of the 1980s, the notion of reserve capacity appears to have given way to discussions of compatibility between two systems. ASCE 7-88 described dual systems as follows:

> 9.9.4 Dual Systems. Dual systems designed using a K-factor = 0.8 or 1.0 shall have moment-resisting space frames conforming to 9.9.3.3 or 9.9.3.4, respectively, that are capable of resisting at least 25% of the prescribed seismic forces. The total seismic force *shall be distributed to* the various resisting systems and elements in proportion to their relative rigidities. (ASCE 1988, p. 39)

Red italics are included here to highlight the moment frame's transition from an independent reserve system to part of the primary lateral system. This implication has been maintained in more recent editions of ASCE 7. ASCE 7-02 listed an Ordinary Concentrically Braced Frame (OCBF) dual system with an intermediate moment frame reserve system and an R-value of 5, allowed in Category D up to 160 ft high and in Category E up to 100 ft high. This system was removed from ASCE 7-05. From the documents discussed above, two conclusions can be drawn:

1. *The moment frame in the dual system was originally conceived as an independent reserve system.* Shake table tests not only validated this concept, but also demonstrated that the reserve system remained essentially elastic. Over the past 20 years, the concept of a dual system seems to have changed into an idea of two different systems working simultaneously. To the authors' knowledge, the literature does not clarify why this change occurred.
2. *The concept of a reserve system has already been demonstrated to be robust.* Reserve systems may even be expected to perform mostly in the elastic range, and therefore they do not need to be very ductile in Design Categories A, B and C. These observations are consistent with the conclusions of Hines et al. (2009).

Moment Resisting Frames and Elastic Flexibility

A recent study by Nelson (2007) compared the seismic performance, according to the FEMA-350 performance assessment procedure (SAC 2000), of the SAC Boston 9-story building with Ordinary Moment Frame (OMF) connections resembling pre-Northridge (MF-Pre) and post-Northridge (MF-Post) conditions. In this study, pre- and post-Northridge were differentiated primarily by the use of notch-tough weld material and removal of the backing bar with weld backgouging for the MF-Post condition. The MF-Pre 9-story moment frame achieved almost 80% confidence of collapse prevention under a maximum considered earthquake (MCE) event, even though it was designed according to Pre-Northridge methods with very little connection ductility. The MF-Post 9-story moment frame achieved 93% confidence of collapse prevention under an MCE event, even after accounting for significant uncertainty related to connection performance. In order to adapt reliability-based performance assessment procedures for use with low-ductility systems in moderate seismic regions, it was necessary to estimate the effects of connection capacity on system collapse capacity. Furthermore, because the systems in question responded in nearly equal measure in the first three modes, it was determined that a richly varying suite of ground motions, which were not scaled at a particular period, would provide the range of excitations necessary to exercise the systems more fully (Sorabella 2006). This variation in the suite of ground motions also helped to account for the greater level of uncertainty of MCE magnitude and distance in moderate seismic regions.

For both MF-Pre and MF-Post systems, the inherent elastic flexibility was found to limit significantly the demands imposed by the suite of ground motions, and it was this flexibility that influenced the overall behavior of the frame. The lack of connection ductility played less of a role, as only one of the 14 ground motions in the suite caused strength degradation in the panel zone model. Similar performance assessments of a stiffer $R = 3$ chevron CBF revealed that as the stiff system attracted higher forces, the low-ductility characteristics of the braced frame became more critical to overall performance. For such a stiff, low-ductility system, the reserve capacity provided by the gravity framing became the primary collapse prevention mechanism (Hines et al. 2009). Since the braced frame was controlled by strength considerations, and was much stiffer than necessary to meet the elastic story drift criterion (in this case h/400) that controlled the moment frame proportions, the braced frame attracted more force than the moment frame under the same design event. Although variability in project-specific drift limits and the stiffening effects of non-structural components introduce uncertainty when drawing conclusions about low-ductility moment frame performance, initial results indicate that the inherent flexibility of moment frames should be carefully considered alongside strength and ductility.

Eccentrically Braced Frames and Ductility

The recent adoption of the Massachusetts State Building Code (MSBC) 7th Edition (CMR 2008) provides a case study for comparing base shears due to wind and earthquake loads and to illustrate the potential for economically designing a ductile lateral system in a moderate seismic region. Hines (2009) provides a detailed description of the changes that occurred between the MSBC 6th Edition (CMR 1996) and the MSBC 7th Edition (CMR 2008). Fig. 3 plots base shear with respect to building height according to the MSBC 7th Edition (CMR 2008) for prototype structures as described by Hines (2009). Wind base shear is compared to seismic base shear for three cases:

1. $R = 3$ CBF where the seismic base shear is determined using the approximate fundamental period, T_a.
2. $R = 3$ CBF where the seismic base shear is determined using the upper limit on calculated period, where T_a is multiplied by a coefficient, C_u, equal to 1.7 in this case.
3. $R = 7$ EBF where the seismic base shear is determined using $T = C_u T_a = 1.7 T_a$.

The $R = 3$ CBF base shears are shown for T_a and $C_u T_a$ since the simpler approach (T_a) seems consistent with the nature of $R = 3$, but the MSBC 7th Edition does not prevent the use of the larger value for the fundamental period ($C_u T_a$) with $R = 3$ structures. Designers would likely use the second approach in order to reduce steel tonnage. Lower forces reduce member sizes and the $R = 3$ provision excuses the structure from any special detailing requirements. Fig. 3 shows that under the MSBC 7th Edition the motivation to pursue seismic detailing, represented by the $R = 7$ EBF, is not strong. Furthermore, the MSBC 7th Edition places most Site Class D structures in Design Category B, increasing the degree to which a designer in the East would tend to disregard the importance of earthquake hazard. At the same time however, the MSBC 7th Edition places restrictions on $R = 3$ systems, including height limits (as shown in Fig. 3) and requires connections to be designed for an amplified seismic force equal to twice the force used for member design. Ironically, recent research indicates that $R = 3$ buildings under 100 ft high appear to be more vulnerable to collapse than taller buildings (Hines et al. 2009). Thus, the

MSBC 7th Edition makes wind even more dominant in the design of structural members but still insists that structures be detailed for a minimum level of ductile capacity. Unfortunately, the type of detailing prescribed has not been clearly established to produce its intended effect with a minimum impact on the cost of the structure. These two circumstances of reduced forces and increased detailing requirements motivated the design exercise and discussion by Hines (2009).

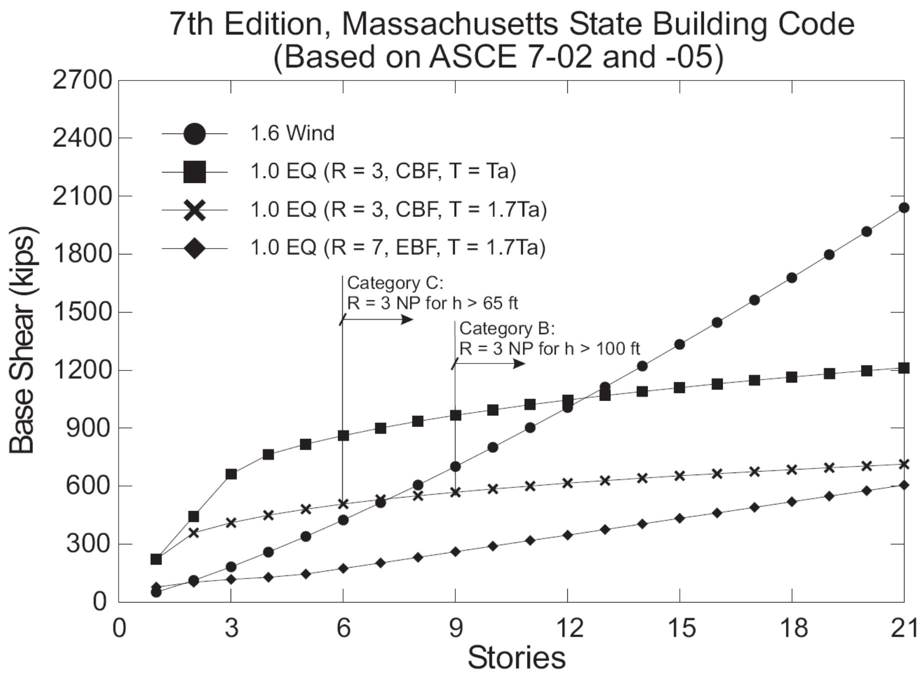

Figure 3. Base shears for wind and seismic loads according to Massachusetts State Building Code 7th Edition (Hines 2009).

Hines (2009) developed a 9-story building design for Boston that demonstrated the potential for using an EBF conforming to the 2005 AISC Seismic Provisions (AISC 2005) without exceeding the weight of an $R = 3$ CBF. Expense incurred via capacity design requirements was kept in check by selecting the smallest possible links to withstand wind forces. These links would be shop fabricated as integral with the beams outside the link. In the field, these built-up link beams and the braces can be erected in a manner similar to a typical CBF with no special detailing requirements. An EBF system, based on this principle of a shop-fabricated weak shear link, is currently under construction for the 3-story, 40,000 sf Dudley Square Police Station in Boston. The winning bid for the project came in approximately two million dollars less than the estimated project cost. Fig. 4 shows a typical link detail from this project.

Although EBF systems promise significantly lower base shears, their branding as “high-seismic systems” has inhibited their common use in Massachusetts. This perception spans across the design and fabrication communities, where the latter perceives shear links to be inherently expensive to detail. Although the increased detailing requirements for ductile links are an added burden for fabricators in the East, it seems likely that the extra cost in this one area can be justified by the benefit they provide with respect to reliable seismic performance. Thus, it is important to consider ductile EBF systems, which are currently only used in the West, as viable solutions for moderate seismic design in the East.

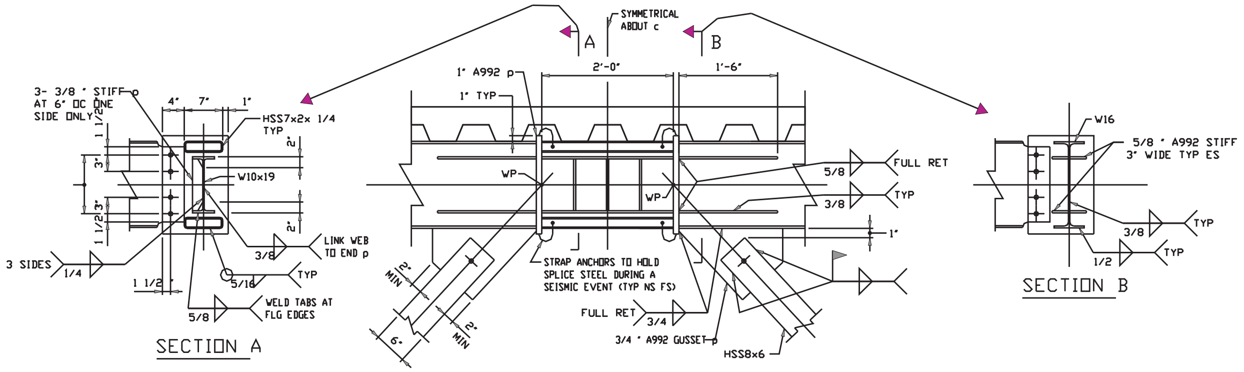

Figure 4. Typical shear link for Dudley Square Police Station in Boston.

Conclusions and Future Research Needs

This paper raises the possibility of transforming seismic steel design in moderate seismic regions through the development of innovative structural configurations based on a new design philosophy. Elements of this discussion have the potential to broaden the impact of earthquake engineering approaches that are common in high seismic regions. A consistent design philosophy for moderate seismic regions has the potential to save lives, conserve resources and enhance creativity in design. As it continues to develop, this new design philosophy must be rigorously grounded in hazard assessment and ground motion development that capture the unique aspects of geology and seismicity found in moderate seismic regions. Numerical and large-scale experimental simulations must be used to evaluate the relationships between strength, ductility and reserve capacity in steel-framed buildings and must lead to reliable performance and collapse prevention.

To calibrate numerical models experiencing brittle damage and higher mode effects, large-scale multi-site geographically-distributed hybrid simulations may be required on a scale that cannot be achieved in a single laboratory. Collapse performance of low-ductility structural systems is highly dependent on ground motion records, which are known to be widely variable in moderate seismic regions and different in character from their western counterparts. Understanding this variability and incorporating it into structural performance assessment requires seamless coordination of disciplines from source to site to structure, and has the potential to advance reliability-based performance assessment in a unique direction.

Findings that are developed for new structures will also benefit assessment of existing structures and maximize the potential for economical and environmentally-responsible renovation and reuse. Effective transfer of research results into practice has already begun in Boston, a city critically impacted by this research.

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