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Sustainable Restoration of Yale University's Art + Architecture Building

RUSSELL M. SANDERS, BENJAMIN SHEPHERD, ELIZABETH SKOWRONEK, AND ALISON HOFFMANN

Renovation of a Modernist icon demanded innovation to restore the original aesthetic while incorporating sustainable-design strategies.

Renovation of Paul Rudolph Hall at Yale University

When Yale University's Art + Architecture Building was completed in 1963, *New York Times* architecture critic Ada Louise Huxtable praised it as "a spectacular tour de force."¹ It appeared on the cover of every major architecture magazine and has since been described as "the Bilbao of its day."² Designed by Paul Rudolph, then chair of the School of Architecture, the Art + Architecture Building is considered one of his most important works. The complex of interlocking spaces and strata catapulted the designer to fame with its assertive treatment of concrete forms (Fig. 1).

By the late 1990s, however, the building had been so altered that it bore little resemblance to its original form. Marred

by a serious fire in 1969, the structure suffered a series of unsympathetic renovations, which split and reconfigured its soaring double-height drafting room and obstructed light and views. The external facade was scarred and barely recognizable after Rudolph's vast fenestrations were filled in with double-glazed windows that were disrespectful of the original geometries. Interior volumes lost their definition not only through unwelcome intrusions and divisions but, more importantly, by removal of the ceiling planes and the signature linear lighting system that defined them.

For the project team in 2006, the task was imposing: restore a controversial, commanding piece of American architectural heritage while introducing new infrastructure and sustainability measures. Previous renovation efforts had aimed to address practical shortcomings in the original design, but the 2008 restoration was the first that sought to honor the Modernist cult figure Rudolph had become after he designed this monument to the architecture department. It was also one of the first to place sustainable-design considerations at the forefront of the renovation effort, a commitment that garnered the project a United States Green Building Council (USGBC) Leadership in Energy and Environmental Design (LEED) Gold certification.

Context

Although Rudolph's design had its defenders, many saw the building's hulking forms and rough textures as abrasive. Since its completion, the iconic building has dominated the downtown commercial district over which it presides. Multiple exterior renovations to the 114,000-square-foot, cast-in-place concrete structure exaggerated its

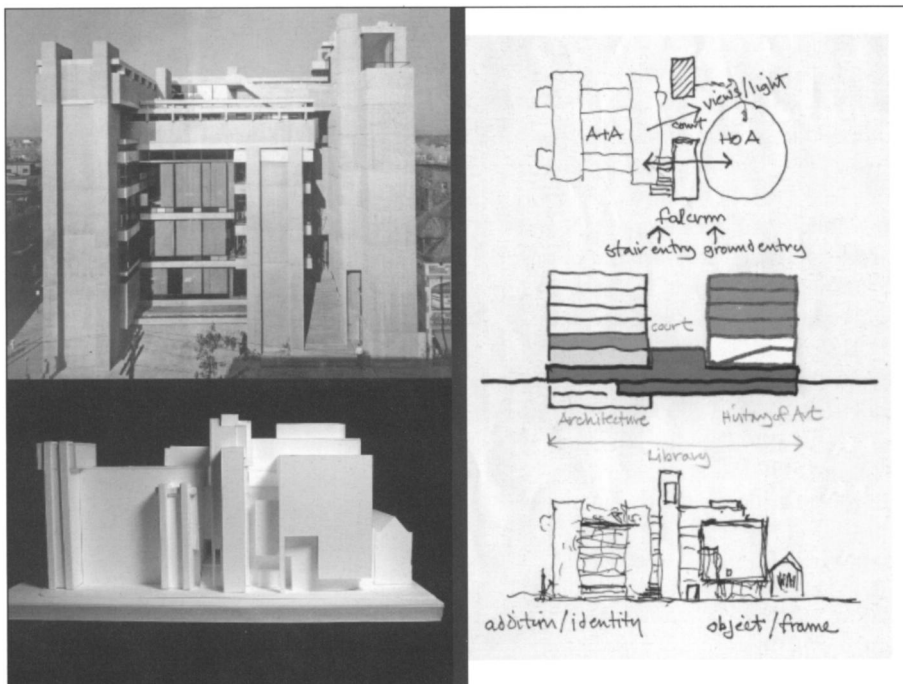


Fig. 1. Yale Arts Complex, consisting of Paul Rudolph Hall and the Jeffrey H. Loria Center for the History of Art. Sketch and model by Gwathmey Siegel & Associates Architects.

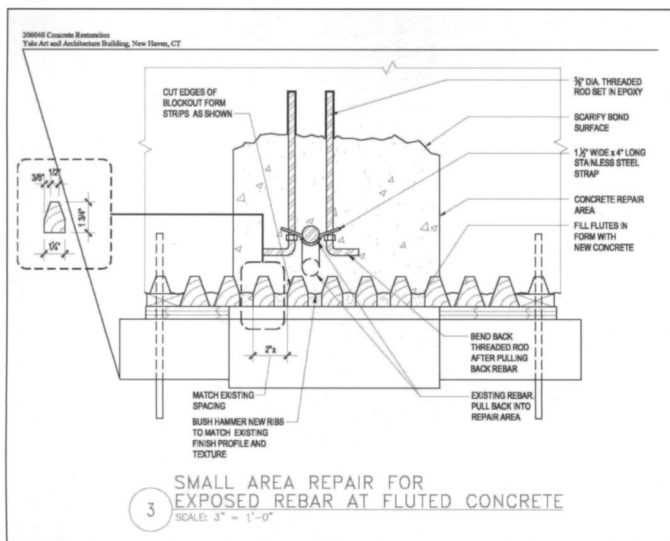


Fig. 2. Schematic of the corduroy-concrete repair detail, showing custom wood formwork, Paul Rudolph Hall. Courtesy of Hoffmann Architects, Inc.

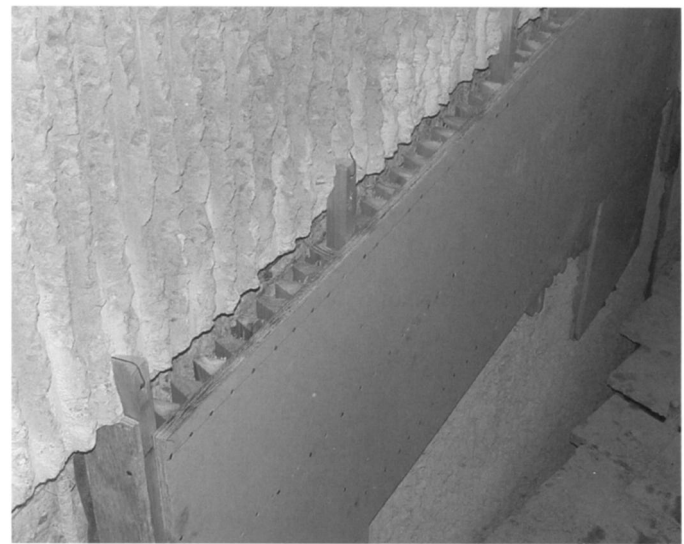


Fig. 3. Wood formwork in position for corduroy-concrete repair, Paul Rudolph Hall, photograph 2008. Courtesy of Hoffmann Architects, Inc.

fortress-like bearing by diminishing views into Rudolph's surprisingly open yet complex interior.

Some of the most egregious interventions included the removal of the original ceiling planes, the insertion of mezzanines into the grand fourth-floor studio volume — the college's solution to overcrowding — and closing off the light wells that in the original design allowed natural light to penetrate deeply into the underground volumes, which were all part of the renovations following the 1969 fire. The original monolithic ceilings, made of asbestos, were removed in the late 1970s. These visually uniform planar ceilings underscored spatial dynamics and served as a plenum for the HVAC, with discreet covers for registers and integrated lighting systems. Rudolph's linear array of bare, incandescent R-lamps served as a volume definition as much as illumination. Stripping the building of these crucial elements slowly transformed it into a poorly lit, nearly hostile environment.

The project team's challenge, then, was to reintegrate the sometimes contentious structure into the community by resurrecting the vision and legacy of Rudolph. In practical terms, this meant incorporating infrastructure upgrades and restoring exposed concrete surfaces, while satisfying the design objectives of the building's occupants: the faculty and students of Yale School of Architecture, as well as the Yale Arts Library.

Application and Intent

The renovation design, which resulted from the integration of programmatic, structural, and mechanical needs, included restoration of exterior walls, installation of historically correct windows, and upgrades to all building facilities. It also introduced new lighting and furnishings throughout and brought the structure into compliance with current building-code regulations.³

Meeting the current codes was especially challenging with respect to the Americans with Disabilities Act (ADA) and fire codes. The original building utilized some 37 different levels over 9 floors, making wheelchair accessibility impossible. In addition, handrails and guardrails either were not present or did not meet code requirements as to size, height, and openness. New handrails were added as needed following the original materials, color, and design geometries; these interventions are virtually unnoticeable unless one looks at the original photographs. Selective changes in the floor levels were also employed to make all spaces fully accessible. The addition of a new elevator bank in the adjacent Jeffrey H. Loria Center for the History of Art, part of the 2008 building expansion, alleviated most of the access issues.

The original building did not employ any sprinklers, and the spatial connections between three or four different levels created fire hazards not permissi-

ble by today's codes. Fire sprinklers with exposed pipes and sprinkler heads were added over the last 20 years, contributing to the overall run-down look of the building. As part of the 2008 work, a new sprinkler system, which employed wall sprinklers to create fire separations between spaces, was added. With carefully selected, discreet locations for the piping, the system brought the building into full compatibility with current fire codes.

The Building Envelope: Consistency and Performance

A 1994 renovation replaced most of the Art + Architecture Building's original steel-framed, single-pane windows with insulating-glass, aluminum-framed units, and in so doing altered the building profile.⁴ Not only were the replacement windows much smaller than the originals, but this renovation attempted to rectify shallow reinforcement placement in the spandrel beams by affixing precast concrete panels to the spandrel face. As a result, the vertical plane of the building was shifted outward by several inches.

Re-creating the appearance of the original fenestration while meeting current energy standards⁵ posed multiple challenges. To fit insulating glass into Rudolph's vast openings, the 1994 window-replacement project had used multiple-pane windows, adding framing

and compromising the original mass and light interplay at the building envelope. The 2008 restoration specified vast glass sheets developed to reduce heat gain and energy consumption. After mock-ups were evaluated for aesthetics and performance, the project team selected a glazing product that provided suitable insulating properties, low-emissivity (low-e), and glare reduction, while reproducing, as closely as possible, the look of the original windows. Fabricated by Viraccon, the 8-by-12-foot panels were some of the largest single sheets of insulating glass ever made in the United States. This change was the single most important aspect of the renovation in terms of the impact on the building's appearance from the street.

What made the restoration of the spandrels particularly difficult was the impressive size of the beams; some spanned as much as 70 feet. Developing a concrete formulation that would replicate the original appearance, hold up well as a thin overlay, and resolve problems inherent to the existing construction was the challenge. Like much of the concrete in the building, the spandrels bore a distinctive finish. Although the structure is known for its corrugated walls, the spandrels had a horizontal board finish that needed to be replicated.

Exploratory window removals revealed that the superimposed precast concrete panels were secured by noncontinuous steel lintel angles attached by stainless-steel anchors to the spandrel beams. When the original window receivers, which were cast into the concrete structure, were removed during the earlier renovation, portions of the spandrel beams were damaged. Even with the most exacting methods, removal of the superimposed precast concrete slabs would likely cause further damage to the original concrete.

To determine the best strategy, the design team completed a series of mock-up concrete tests. After testing, the following approach was agreed upon. First, the original concrete slab would be cut back and prepared, leaving a fractured aggregate surface for adhesion of the repair material. Steel reinforcements would then be treated where possible, replaced, or reinforced and would be positioned to ensure appropriate con-

crete coverage. Wood forms for the concrete overlay would be anchored to the spandrels, with bolts positioned to replicate the size and spacing of anchor holes on the original beams. Using hooked rods, a mesh screen would be secured to the substrate both as reinforcement and as protection against shrinkage.

Specifying the right concrete mix was the challenge. The building profile allowed only a few inches of depth for repair of the spans. To reduce the possibility of hairline cracks, the designers' first approach used large, preplaced aggregate and pumped the concrete mix up through the bottom of the formwork. However, mock-up tests showed that pressure within the narrow forms became great enough to force the concrete mix out through joints in the wood. Voids between the large pieces of aggregate were also an issue.

To accommodate the restrained conditions, as well as the multistory ascent from the mix truck, the project team developed a high-performance, small-aggregate mix.⁶ A low water-to-cement ratio, combined with a proprietary anti-shrink admixture, performed well in petrographic, air content, and compression-strength laboratory testing.⁷ To reproduce the original surface texture, 2¼-inch-wide tongue-and-groove red oak flooring planks, unfinished and unsanded, were used for the formwork. Mock-ups closely approximating the concrete mixture and techniques to be used in construction were used to identify a suitable color match.

To evaluate the proposed window and spandrel design for water and air infiltration, mock-ups of the entire window assembly, including glazing, framing, mullions, and concrete spandrel beams, were evaluated at an off-site architectural-testing facility. Based on the results of this testing, adjustments were made to the perimeter-seal system to improve adhesion to the concrete and prevent water infiltration.

What the mock-ups could not reproduce was the extremely long length of the spandrels, as well as their height from the ground. A continuous-pour technique was used to set the concrete evenly across the span. Despite concerns that such an expanse could show cracking every few feet, the final product has



Fig. 4. View of fourth-floor jury space and fifth-floor studio space, including the statue of Minerva, Paul Rudolph Hall. Photograph by Richard Barnes.

held up beyond expectation, with only negligible hairline cracks.

Like the board-form spandrel beams, the distinctive “corduroy”-textured concrete suffered from poor construction practices. Shallow placement of steel reinforcement, with an inch or less of concrete protection in many areas,⁸ had led to corrosion, cracks, and spalls. Restoration involved removal of the delaminating concrete, repair and treatment of embedded steel, and re-covering of the steel reinforcement to an appropriate depth with color- and texture-matched concrete. Approximately 500 square feet of fluted concrete throughout the structure was restored using this repair strategy.

Because the corrugated vertical ribs were not uniform in dimension, custom formwork had to be created for each area of repair (Figs. 2 and 3). Here again, developing and testing a concrete mix that would replicate the original appearance, hold up well as a thin overlay, and resolve the problems of the existing construction was the challenge. Concrete was placed by hand into the fluted forms, with individual pieces of aggregate forced between block-outs into the mix. To properly consolidate the material, the concrete-restoration

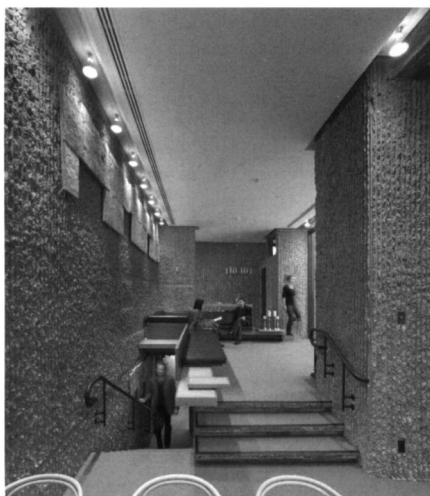


Fig. 5. Custom lighting in the restored penthouse, Paul Rudolph Hall, photograph 2008. Photograph by Peter Aaron, courtesy of Peter Aaron/Esto.

contractors used a needle-type vibrator along the formwork, then tapped the outside of the form with a mallet to minimize surface bubbles. Bush hammering of finished repair areas reproduced the fluted concrete's distinctive rough surface texture.

One of Rudolph's innovations in the Art + Architecture Building was the use of light wells, voids that admitted light from the sidewalk level down into vertical windows in two subgrade stories. In an earlier effort to address leaks and drafts, these spaces were covered over with roofing materials. In restoring the light wells, the project team removed the superimposed roof, recast the multilevel terraces and planters, reintroduced original sculpture installations, and recreated the windows using insulating glazing. Attention to flashing details, terminations, and proper sealant application at frame perimeters solved moisture-entry problems while permitting natural light to once again permeate even the subbasement. By relocating mechanical equipment into the north end of the building, the architects were able to locate model-shop areas to benefit from the reintroduced light wells.

Roofs also suffered the effects of time, weather, student abuse, and failed repairs. Leaks had become pervasive. To restore roof terraces as usable outdoor areas, reflective pavers⁹ were installed over a modified bitumen roof (MBR) membrane assembly, with new planters

and seating throughout. Period photographs show that the original terrace pavers, which were not in place at the time of the 2008 renovation, followed a running-bond pattern, and the new pavers were installed to reproduce this configuration. Roof areas not open to public traffic have cold-adhesive MBR assemblies with white granular cap sheets to reduce heat absorption.¹⁰ As multilayer systems, MBR membranes resist puncture and provide waterproofing redundancy; bituminous compounds also offer flexibility and self-healing properties,¹¹ qualities critical to durability and, consequently, sustainability of the roof assembly.

Leaks were also an issue at the building's complex and massive skylights. Central to the building's treatment of light and space, the compound skylights join multi-planar glazing to counterpoint the densely textured concrete slabs. As part of the 1994 window rehabilitation, the original single-pane skylights were replaced with insulating glass. By 2006 these replacement skylights exhibited leaks, etched glass, and a generally dilapidated appearance. The 2008 restoration removed the 1994 assembly and replaced it with a new system that matched framing spacing, profile, and glass sizes as closely as possible to those depicted in Rudolph's drawings, while resolving leaks, heat loss, glare, and excessive solar heat gain inherent to the original design. To accurately replicate the original dimensions, the project team could not rely on stock products; custom framing and anchoring systems secured the heat-treated, laminated insulating glazing units. Aesthetically the 2008 renovation aligned additional joints necessitated by the insulating glass with an interior partition, so that from below, the glass appeared to extend up and over the wall. From above, clunky 1994 mullions were replaced with a simple butt joint, so that the glass seemed continuous when viewed from the terrace, as well. Waterproofing details were also improved. The 1994 replacement failed to take into account the higher profile of the insulating-glass assembly when providing flashing details; the 2008 project extended flashings at exterior walls to protect against moisture intrusion. Gutter linings, extra drains, and addi-

tional drainage slope further improved water management during weather events.

At building entrances, existing doors showed signs of pervasive corrosion, drafts, and deformation and required replacement in kind. New steel doors were filled with a rigid polyurethane core, which was chemically bonded to the interior surfaces of the door and had steel stiffeners for structural support.¹² For glazed entrance doors, the project team specified a laminated infill glass with a polyvinyl butyral (PVB) interlayer for safety, durability, and shatter resistance. Existing concrete frames and openings were retained and restored.

Interiors: Space and Light

Past renovations had severely altered the building's once-soaring spaces, slicing the double-height drafting room into separate levels and creating uncomfortable, dim rooms. To re-create the original balance of light and shadow, as well as volume and void, the project team removed the mezzanines that had been inserted after 1969 and divided the space. Most notably, the drafting room at the building's core was restored with the removal of the mezzanines, which allowed daylight into the space. A replica of the original statue of Roman



Fig. 6. Installation of new insulating glazing at the east facade, Paul Rudolph Hall, photograph 2008. Courtesy of Hoffmann Architects, Inc.



Fig. 7. Fourth-floor terrace and green roof, Paul Rudolph Hall, photograph 2008. Photograph by Peter Aaron, courtesy of Peter Aaron/Esto.



Fig. 8. Robert B. Haas Family Arts Library, Paul Rudolph Hall addition, photograph 2008. Photograph by Peter Aaron, courtesy of Peter Aaron/Esto.

goddess Minerva was restored to her post overlooking the great hall (Fig. 4).

The terraced floor plan, with 37 levels on 9 stories, had long caused problems regarding accessibility. The renovation was able to meet relevant ADA guidelines¹³ and building codes,¹⁴ so that the building is completely accessible. Ramps and handrails in the fourth-floor studio blend into the existing spaces. While the jury spaces on the sixth and seventh floors were raised to match the level of the surrounding studios, they remained delineated through a change in flooring material.

Despite their heft, the interior exposed-concrete slabs had not been immune to the effects of time, student abuse, and failed repair efforts. Many surfaces were worn and covered with paint, graffiti, and stains, which created a mottled look. To restore a uniform appearance, cleaning needed to penetrate roughly textured concrete without damaging the surfaces. Because the university wished to retain certain graffiti that it deemed historically significant, the strategy would also need to be selective.

The cleaning program began with detailed documentation of locations and types of dirt and coatings (e.g., paints, wax, dirt, finishes). Approximately 7,200 square feet of bush-hammered concrete and 9,000 square feet of board-formed concrete required cleaning, in addition to more than 80,000 square feet of floor area. Mock-up tests with removers, strippers, and solvents were prepared to select the best product for

each application.¹⁵ Cleaning not only uncovered original coloration; it also helped to blend repair areas into surrounding surfaces by improving uniformity of hue in the existing concrete. Colors for the repair mixes could then be matched to clean, not soiled, concrete. Care was taken, however, not to be overly aggressive with the cleaning program. Products were chosen to be non-abrasive and non-bleaching, as the priority was to remove dirt and unwanted coatings, not to achieve a “brand new” concrete appearance.

Special attention was paid to interior lighting. Using Ezra Stoller's period photographs, the architects modeled both new and existing spaces to understand lighting quality. Custom fixtures with metal halide lamps replicated the appearance of the original incandescent lights, but they consume only 39 watts, rather than 150 (Fig. 5). Aluminum reflective paint, vernal lenses, and prismatic lamps result in a scattered-light effect that reproduces Rudolph's design intent, with vastly improved energy performance.

City residents and students of architecture remember well the original vibrant orange carpeting, and this key design element was revived. From a single, small surviving sample, the architects were able to match new carpeting to again provide a warm counterpoint to the building's rough concrete. Authentic mid-century Modern furniture was specified, and a number of original pieces were replicated.

Sustainable-Design Strategies

As the National Trust for Historic Preservation has argued, “the greenest building is the one that already exists.”¹⁶ Increasingly, the sustainable-design field is bringing this concept to the fore, applying today's design and energy standards to existing buildings without compromising the original project vision. When the renovation of the Art + Architecture Building began, Yale had already developed and implemented significant sustainability initiatives, most notably a mandate of minimum LEED Silver certification for all major construction projects on campus. However, at the time, it was unknown how these goals might be applied to the renovation of existing structures. As both a historically important building and the center of architectural study at the school, the Art + Architecture Building represented the ideal opportunity to showcase the university's commitment to sustainable building.

The project exceeded expectations. The building achieved LEED Gold certification and integrated environmental strategies that made sense for the structure and circumstances. Historically accurate but inefficient elements, such as oversized glazing or low-insulating concrete walls, were offset by innovations in low-e insulating glass units, high-efficiency HVAC systems and controls, daylighting and occupancy sensors, air handling, storm-water management, non-potable water reuse, and existing site redevelopment.

Resource conservation. More than 90 percent of existing walls, roofs, and floors were preserved during the renovation. Sustainable construction practice recycled or salvaged 92 percent of construction waste, diverting 4,150 tons of debris away from landfills. Replacement materials were selected for high content of recycled material, and more than a third of project materials were locally sourced (within 500 miles). Forest Stewardship Council (FSC)–certified wood products were specified for the interior, and all composite wood materials contain no added urea-formaldehyde, a known carcinogen.

Building-envelope performance. Improving building-envelope thermal performance is the most basic way to increase the energy efficiency of virtually any building, and this project was no exception. The building's continuous southwestern exposure, along with the unfortunate window replacement of the 1990s, left interior spaces, many of them faculty offices, prone to overheating. New double-glazed windows insulate against heat transfer, while a spectrally selective low-e coating admits daylight with an appropriate level of solar control. Not only does the improved glazing dramatically reduce summer cooling loads and retain interior heat during the winter; it reduces electric-lighting costs and restores occupants' connections to the outdoors.¹⁷ With unobstructed, sweeping views and meticulously detailed anchorage and framing, the redesigned glazing was designed to optimize performance with respect to insulation, moisture, and daylight (Fig. 6).

At the roof level, installation of tapered polyisocyanurate board insulation and rigid extruded-polystyrene insulation at terraces improved energy performance by preventing heat loss through the roof. Fully abutted, parallel courses with staggered joints were specified to minimize heat transfer between boards. Existing roofing was replaced with roofing with a high solar reflectance index (SRI), which incorporates reflective granules into white cap sheets. By reflecting much of the sun's UV radiation, the light-colored roofs keep both the building and the surrounding area significantly cooler. The Art +

Architecture Building is situated in an urban area, where there is little greenery and a large amount of heat-absorbing concrete and asphalt. Adding reflective cap sheets and light-colored terrace pavers helps to cut down on the "heat island effect," whereby the temperature of metropolitan areas is higher than that of the surrounding countryside.

Mechanical/electrical/plumbing efficiency. Earlier renovations of Rudolph's building had not solved the challenge of heating and cooling in a way that adequately addressed occupant comfort yet respected the open volumes of the building plan. The existing HVAC system had never functioned properly. New slim, ceiling-mounted radiant panels, which use water rather than air for heating and cooling, were installed in 2008 and defer to the spatial relationships of Rudolph's design. Fed by piping rather than by ductwork, the panels are suitable for areas with extremely limited floor-to-floor heights. This system allowed for the reintroduction of original ceiling planes, which are important to proper light distribution within studio spaces. Utilizing economies of scale, the system relies on centrally generated hot and cold water. Working in concert with linear diffused air circulation, the panels do not need a fan to operate, providing energy savings and quieter operation than traditional HVAC equipment.

Air-handling units in the lecture hall and classrooms are equipped with enthalpy heat exchangers, which salvage energy from returned building air and transfer it to incoming fresh air. Because energy is transferred rather than expelled, the exchangers reduce heating and cooling loads, improving energy efficiency in these large and variably occupied spaces.

A three-dimensional MEP coordination process utilizing Revit software streamlined development and installation for optimal functionality. To respond dynamically to building usage, Aircuity, an air-quality system, monitors carbon dioxide levels and reduces ventilation rates when rooms are unoccupied. The system also improves the control of temperature and humidity levels and monitors levels of particulates and volatile organic compounds.

Lighting control. In addition to a 75 percent reduction in wattage over standard incandescent fixtures, the ceramic metal halide lamps in the studio spaces and the great hall use an alternate switching pattern based on daylight levels to minimize energy consumption. In perimeter areas, linear fluorescent lamps dim in response to daylight, and all inside fixtures are positioned to shine toward the building interior, rather than out through windows. Exterior fixtures are full cutoff, directing light at the ground, not into the sky. Lighting power densities are kept at low levels to minimize light pollution, while maintaining the look of the historic Rudolph lamps with a new, more energy-efficient fixture.

Water management. The project team implemented extensive water-conservation measures to drastically reduce the use of potable water. Water-saving fixtures alone will save an estimated 13,000 gallons of potable water every year. A small, 2,300-square-foot green roof and on-site storm-water retention, storage, and reuse save a projected 72,000 gallons off stormwater runoff, which is filtered for use in toilets and irrigation. With a 77 percent reduction in run-off, the reclaimed-water system helps prevent municipal treatment facilities from becoming overwhelmed in heavy rainfall (Fig. 7). Previously, storm water from the site had been directed to a combined storm drain and sewer system. To combat the detrimental impact of combined sewer overflow, the renovation project accessed a separate storm-water line, from which run-off can be safely channeled into the municipal sewer system without exacerbating overflow conditions during major storm events.

Community

As an integral part of Yale's arts campus, as well as New Haven's busiest streetscape, Rudolph's masterwork is contextualized both by its history and by its relationship to the diverse community it serves. To support the local economy, the project team utilized local labor and materials wherever possible. Construction engaged more than 25 percent of its workers from minority- or woman-owned businesses and from

New Haven, accumulating approximately 82,979 local man-hours and 144,143 minority man-hours. Local workers earned more than \$2 million in wages. First-year trainees in minority apprenticeship programs also supported the City of New Haven by helping to develop the local trade force.

Former students of Rudolph, Yale School of Architecture Dean Robert A. M. Stern and project design principal Charles Gwathmey were committed to applying their mentor's aesthetic to the renewal of his seminal work (Fig. 8). However, the timeline for achieving this goal was extremely short. Yale did not intend to displace the School of Architecture for more than one academic year, which meant that once classes ended in May 2007, the team had less than 15 months to complete the project. Nevertheless, the project was completed on time, within budget, and to exacting quality standards. To honor its famed designer, the university rededicated the building as Paul Rudolph Hall.

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Notes

1. Robin Pogrebin, "Renovating a Master's Shrine: Yale's Art and Architecture Building," *New York Times*, July 1, 2006.
2. Kate Taylor, "Pennies to Build, Millions to Restore," *New York Sun*, Nov. 26, 2007.
3. The State of Connecticut uses the 2003 *International Existing Building Code*, developed by the International Code Council, along with a Connecticut-specific edition of the 2003 *International Building Code*.
4. Michael J. Crosbie, "Yale Art and Architecture Building," *Architecture Week*, Feb. 4, 2009, www.architectureweek.com.
5. See "Chapter 5: Commercial Energy Efficiency," 2009 *International Energy Conservation Code (IECC)*, International Code Council, Feb. 2009, and ASHRAE 90.1-2004.
6. The concrete formulation for the board-form repairs (approximate) consisted of rapid-set DOT cement, pea gravel (maximum 3/8-inch diameter), water, sand, flow-control admixture, set-control admixture, corrosion inhibitor, color pigment, and air entrainment of 6 percent. Fluted concrete repairs used 3/4-inch aggregate; otherwise the formulation was the same.
7. Petrographic laboratory analysis of a 6-inch hardened concrete core 2 3/4 inches in diameter was performed in accordance with *ASTM C856 Standard Practice for Petrographic Examination of Hardened Concrete* and *ASTM C457 Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete*. Aggregate size and composition, color, slump, paste hardness, depth of carbonation, water-to-cement ratio, and air entrainment were evaluated by an independent, off-site petrographic testing facility. Compression tests of 6-by-12-inch cylinders were also conducted off-site at a testing laboratory, in accordance with *ASTM C39 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*.
8. The American Concrete Institute standard *ACI 318-08: Building Code Requirements for Structural Concrete* and the 1963 version, *ACI 318-63*, both call for "not less than 2 in. of concrete for bars larger than #5 and 1 1/2 in. for #5 bars or smaller;" *ACI 318-63*, Section 808 and *ACI 318-08*, Section 7.7.1. These publications are available through the American Concrete Institute.
9. The average light absorption of the reflective pavers was 5 percent, with no unit greater than 7 percent when tested in accordance with *ASTM C 140*.
10. The white granular surfacing meets the LEED SRI minimum of 78.
11. *ASTM D5147 Standard Test Methods for Sampling and Testing Modified Bituminous Sheet Material*.
12. See Table 502.3, 2009 *International Energy Conservation Code (IECC)*, International Code Council, which recommends a maximum U-factor of 0.80 for entrance doors; the steel doors used at Rudolph Hall have a maximum U-factor of 0.10 (equivalent to a minimum R-value of 10).
13. See "ADA Accessibility Guidelines for Buildings and Facilities (ADAAG)," U.S. Architectural and Transportation Barriers Compliance Board, 2002, <http://www.access-board.gov/adaag/html/adaag.htm>.
14. The State of Connecticut Building Code uses ICC/ANSI A117.1-2003, "Accessible and Usable Buildings and Facilities." See State of Connecticut Department of Public Safety, Office of the State Building Inspector, <http://www.ct.gov/dps/cwp/view.asp?a=2148&q=305412>.
15. Light staining was treated primarily with a proprietary low-acidity gel cleaner containing glycolic, amidosulfonic, and hydrofluoric acids, while heavy encrustation demanded a more strongly acidic cleaning formulation that combined glycolic acid with a hydrogen chloride solution. Multiple layers of paint and graffiti were removed with alkaline organic solvents, including potassium hydrate, ammonia, and dipropylene glycol methyl ether (DPM), neutralized afterward with mildly acidic wash. Because the Yale School of Architecture wished to preserve the history of the building, the goal of the cleaning program was not to make everything look new. The sensitive cleaning approach was selective, leaving some paint and graffiti intact while removing unwanted coatings. The program involved a combination of cleaning products and low-pressure water wash to achieve the desired effect.
16. Richard Moe, "Sustainable Stewardship: Historic Preservation's Essential Role in Fighting Climate Change," *Connecticut Preservation News* 31, no. 4 (July/Aug. 2008): 6.
17. Atelier Ten evaluated the project's energy performance using eQUEST v3.61, an advanced whole-building energy-simulation tool. The new Viracon VE1-2M glazing reduced peak space cooling by an estimated 49 percent and helped contribute to the building's overall energy savings of 14 percent relative to a code baseline building.



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