was dynamited by demolition specialists in the 1960s in such a spectacular show that to this day it is frequently shown on national television. The Bridge of Santa Trínita over the Arno River in Florence, the sixteenth-century masterpiece of Bartolomeo Ammannati, was ruthlessly dynamited during the Second World War by the retreating Nazis, despite heroic efforts to save it by the Italian partisans. Its reconstruction after the end of the war as an exact replica of the original was paid for by an international subscription.

We mention on p. 239 the destruction of the Cathedral of Coventry in England during World War II, but it would take a separate volume to list all the historical or otherwise significant structures destroyed by the wars men have fought. Hence we shall end our description of willful demolition by mentioning the recent case of four houses in the Times Square area of New York City that is particularly significant both because one of these structures had housed the temporarily homeless and because the demolition was sneakily executed at night just a few hours before a freeze prohibiting all demolition was due to be imposed by the city. Although the developer responsible for this action was fined two million dollars by the city's building authorities, he was allowed to build on the site so cleverly "cleared" a high-rise hotel worth hundreds of millions of dollars.

Thus do nature, time, incompetence, human folly, and greed conspire to tear down structures man has spent so much love, time, thought and energy to put up.

15

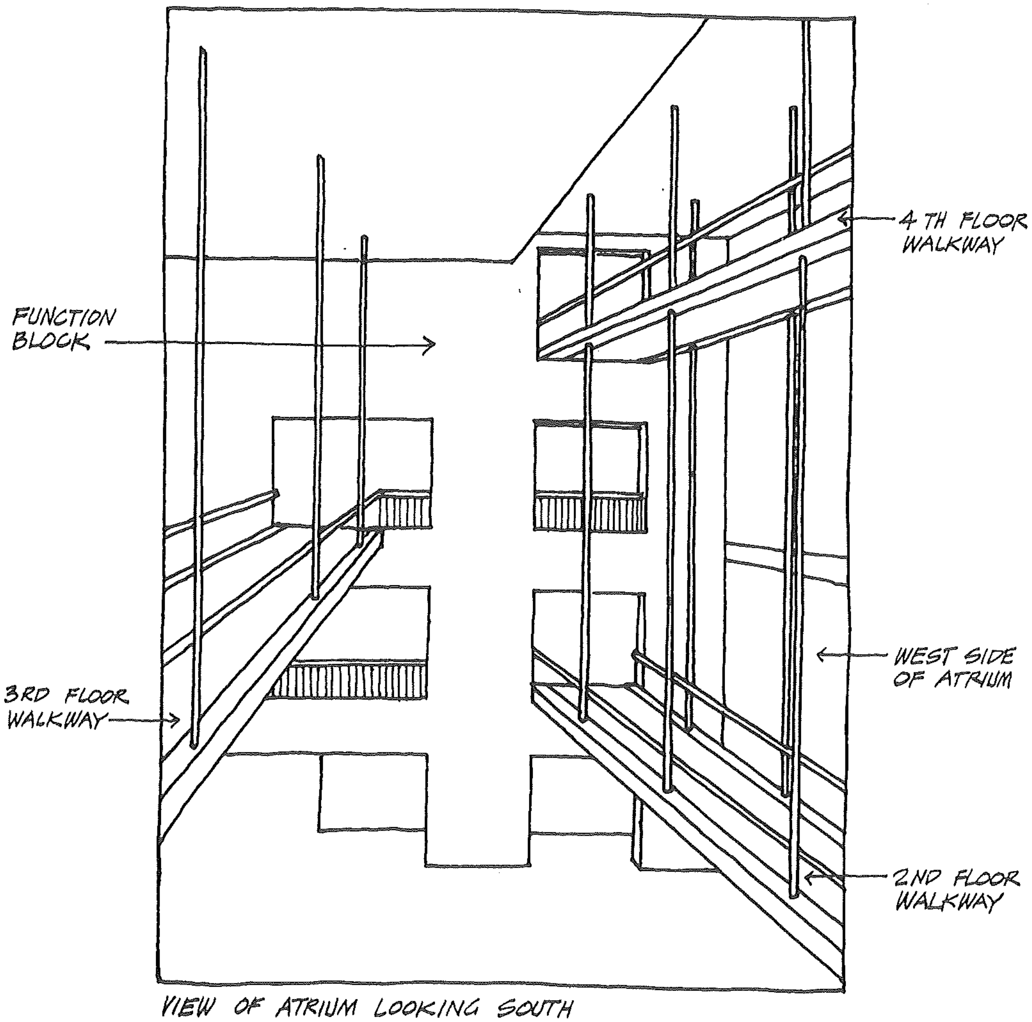
The Worst Structural Disaster in the United States

The bad end unhappily,
the good unluckily.

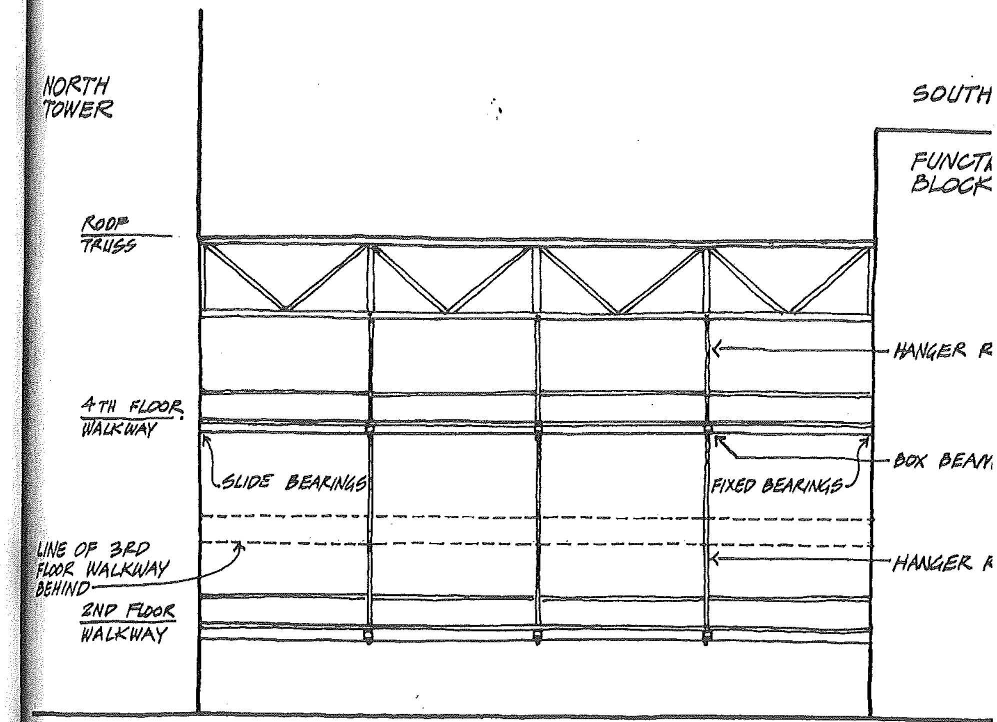
Tom Stoppard,
Rosenkranz and Guildenstern Are Dead

In July 1980 the plushiest and most modern hotel in Kansas City, Missouri, the Hyatt Regency, was ready for occupancy after two years of design and two more years of construction. Kansas City's "first citizen," Donald Hall, of Hallmark greeting cards fame, bought it from the developers, and his management company started one of the most ambitious and popular programs to be found in an American deluxe hotel. Service in the 750 rooms and suites was refined and fast, food in the many restaurants exquisite, and the tea and dinner dances in its grandiose atrium were soon attended by elegant crowds.

The Hyatt Regency complex consists of three connected buildings: a slim reinforced concrete tower on the north end, housing the guests' bedrooms and suites; a 117 by 145 ft. (34 × 44 m) atrium with a steel and glass roof 50 ft. (15 m) above the floor; and at the south end a four-story reinforced concrete "function block," containing all the service areas—meeting rooms, dining rooms, kitchens, etc. (Fig. 15.1). The tower was connected to the function block by three pedestrian bridges, or *walkways*, hung from the steel trusses of the atrium roof: two, one above the other, at the second- and fourth-floor levels near the west side of the atrium and one at the



15.1 Atrium of Hyatt Regency Hotel, Kansas City, Missouri



15.2 Elevation of West Side Atrium Showing Second- and Fourth-Floor Walkways

third-floor level near the east side of the atrium (Fig. 15.2). Restaurant service was available at a bar set *under* the two stacked walkways on the west side of the atrium. The main purpose of the walkways was to permit people to pass between the tower and the function block without crossing the often crowded atrium.

At 7:05 P.M. on Friday, July 17, 1981, the atrium was filled with more than sixteen hundred people, most of them dancing to the music of a well-known band for a tea dance competition, when suddenly a frightening, sharp sound like a thunderbolt was heard, stopping the dancers in mid-step. Looking up toward the source of the sound, they saw two groups of people on the second- and fourth-floor walkways, observing the festivities and stomping in rhythm with the music. As the two walkways began to fall, the observers were seen holding on to the railings with terrified expressions on their faces. The fourth-floor walkway dropped from the hangers holding it to the roof structure, leaving the hangers dangling like impotent stalactites. Since the second-floor walkway hung from the fourth-floor walkway, the two began to fall together. There was a large roar as the concrete decks of the steel-framed walkways cracked and crashed down, in a billowing cloud of dust, on the crowd gathered around the bar below the second-floor walkway. People were screaming; the west glass wall adjacent to the walkways shattered, sending shards flying over 100 ft. (30 m); pipes broken by the falling walkways sent jets of water spraying the atrium floor. It was a nightmare the survivors would never forget.

The following day the press mentioned 44 dead and 82 injured, but the last victim to be reached alive, a World War II navy pilot who was in a wheelchair on the second-floor walkway, succumbed from chest injuries five months later. The final count reported 114 dead and over 200 injured, many maimed for life. It was indeed the worst *structural* failure ever to occur in the United States. The plaintiffs' claims, also the largest ever in a structural failure case, amounted originally to more than three billion dollars. Donald Hall settled more than 90 percent of these claims out of a sense of duty and social responsibility.

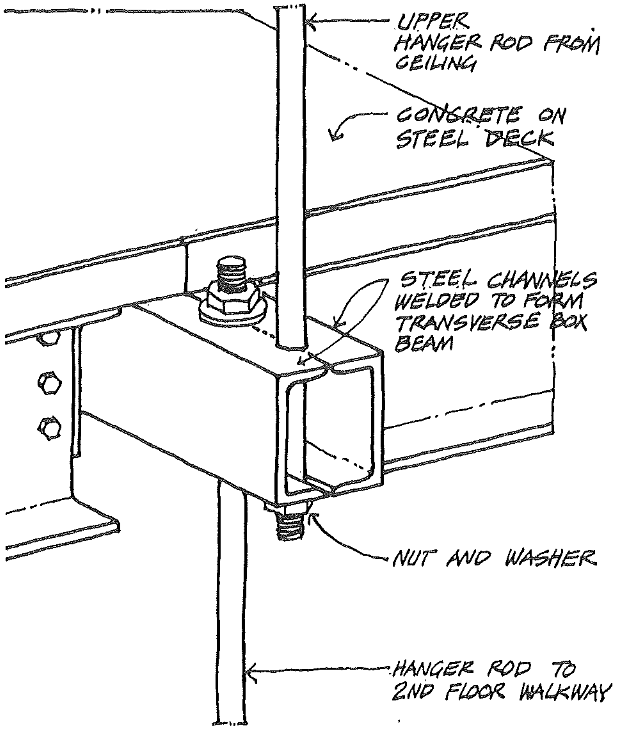
Within a few hours of the accident rumors about the cause of the failure began to fly. As usual, the general contractor and his subcontractors were the first to be suspected of malfeasance and malpractice. Then technical opinions blossomed. Since the people on the two walkways were stomping in rhythm with the music, *obviously* the up-and-down vibrations of the walkways must have had *exactly* the same rhythm; technically, they were *in resonance* with the impacts of the stomping people, and, as *everybody knows*, continued resonance can quickly destroy even a sound structure (see p. 272). Then engineers and laypeople began suspecting the quality of the materials used in the walkways (*everybody knows* that weaker materials are cheaper than good materials) or the skills of the workers who welded and bolted them together *(everybody knows* that skilled workers demand higher salaries than *unskilled ones)*. For a relatively long time the only unsuspected members of the construction team were the architects and the design engineers.

The management company of the hotel was the first to take action. It asked the design team of the hotel to prepare the drawings for a second-floor walkway *supported by columns* and authorized its immediate construction. Simultaneously it entrusted to Weidlinger Associates a most thorough analysis and check of the entire structure of the hotel complex (except the walkways), from the rotating restaurant at the top of the tower to the spiral cantilevered stairs connecting the upper three floors of the function block with the atrium floor, to the foundations of the three components of the complex. Shortly thereafter, at the request of the Kansas City mayor, the federal government authorized the National Bureau of Standards to perform an official investigation with "the objective of determining the most probable cause of the collapse." E. O. Pfrang and R. M. Marshall of the bureau, two well-known and highly respected engineers, performed an in-depth investigation, using theoretical calculations and experimental verification of the walkways components, and issued an official report in 1981. As is its custom, the bureau did not assign blame to any party but made it clear that the responsibility for the collapse could mainly be attributed to the structural engineers, who eventually lost their licenses in the state of Missouri.

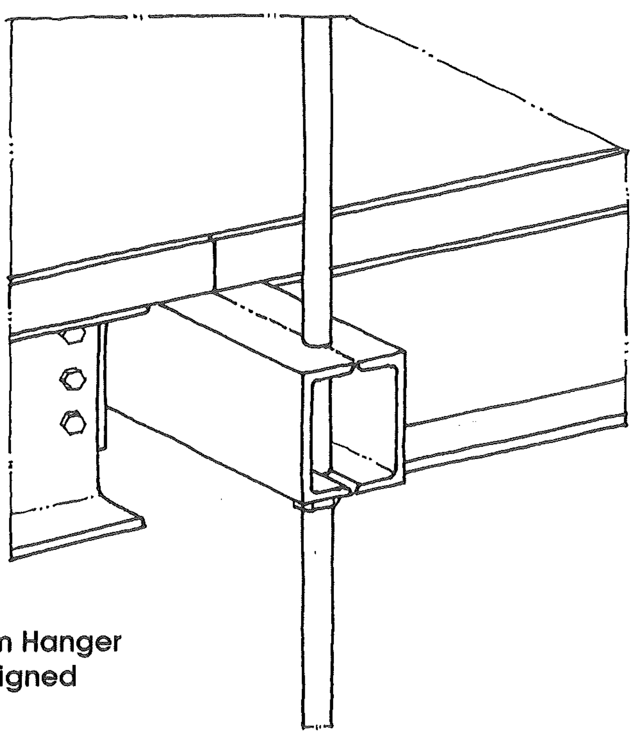
How could this tragedy have occurred in the year 1981 in the most advanced technical country in the world and after two years of design and two of construction? In order to clarify this mystery, we must understand how the walkways were originally designed and how they were eventually built.

The two walkways on the west side of the atrium involved in the collapse (the third-floor walkway that was separately hung remained in place) consisted of four 30 ft. (9 m) long spans on each side, consisting of two longitudinal wide-flange steel beams each 16 in. (400 mm) deep. The four 30 ft. (9 m) beams were connected by steel angles bolted to the upper flanges at the beams' ends, thus spanning the 120 ft. (36 m) atrium width (Fig. 15.2). The south ends of the walkways were welded to plates in the floors of the function block, and their north ends were supported on sliding bearings in the floors of the tower. The purpose of the sliding supports was to allow the beams to expand or contract with temperature changes without giving rise to thermal stresses (see p. 274).

Intermediate supports of the walkways at each end of the 30 ft. (9 m) beams consisted of transverse *box beams*, fabricated by butt welding along their entire length two 8 in. (200 mm) deep channels (Fig. 15.3). In the *original working drawings* (the last engineering drawings submitted to the contractor and the architects by the design engineers) each box beam had *single* holes at both ends of the flanges (Fig. 15.4), through each of which was threaded a single 1¼ in. (32 mm) steel rod that served as hanger for *both* the second-



15.3 Box Beam Hanger Detail—as Built



15.4 Box Beam Hanger Detail—as Designed

and fourth-floor walkways. In this design the load of *both* walkways was supported every thirty feet by means of nuts screwed into a *single* rod on each side of the walkways at the level of the second-floor *and* the fourth-floor box beams. Thus the single rods hung from the steel trusses of the atrium's roof supported the weights of *both* walkways, but the box beams of *each* walkway supported only the loads on *that single walkway*.

In the *shop drawings* (the final drawings submitted by the contractor to the design engineers and the architects) each end of the *fourth*-floor box beams had *two* holes through both flanges, one at 2 in. (50 mm) from the end and the other at 6 in. (150 mm) from the end (Fig. 15.3). Two *upper* hangers, ending at the fourth-floor level and consisting of 1¼ in. (32 mm) rods, went through the *outer* hole in each box beam of the fourth floor and supported the *fourth-floor walkway only* by means of nuts and washers at their *lower* end—i.e., *below* the box beams of the fourth-floor walkway. Two separate *lower* rod hangers, starting at the fourth-floor level, went through the *inner* hole of each fourth-floor box beam, supported by a nut and washer at their *upper* ends—i.e., *above* the fourth-floor box beam—and supported at their lower ends the second-floor walkway. This design was a change suggested by the contractor in the *shop* drawings and stamped "Approved" by the architects and "Reviewed" by the structural engineers. (Design engineers are advised by their attorneys never to stamp the contractor's shop drawings "Approved".) In the final contractor's design the loads of *both walkways* was transmitted to the roof trusses by the shorter upper rods, which passed through *only the fourth-floor box beams* and supported the second-floor walkway by two additional shorter rods hanging from the fourth-floor box beams. Thus in this design the fourth-floor transverse box beams supported the loads of *two* walkways, rather than the *one* of the original design.

At this point the reader will probably think: "By now I know why the tragedy occurred. The box beams of the fourth-floor walkway were designed to carry the load of one walkway and instead had to carry twice that load. No wonder they failed!" That would not be wrong, but neither would that be completely right, as the in-depth investigation of the National Bureau of Standards proved to laypeople and engineers alike.

The job of Pfrang and Marshall might be thought relatively simple: to determine whether the rods and the box beams of the final design could resist the tension in the rods and the bending in the box beams from the hanging walkways. For this purpose they determined the *dead load* of the walkways by taking from engineering manuals the weight of each walkway component and adding them up. But they also weighed the components recovered from the collapse and found that the dead load was actually 8 percent higher than the computed load, because the deck of the walkways consisted of a corrugated steel deck and 3¼ in. (82 mm) of concrete, *plus* a cement topping not shown on the drawings but authorized in the *specifications* (the written document describing each component of the project accompanying the final engineering drawings). The *live load* was required by the Kansas City Building Code to be 100 lb./sq. ft. (5 kN/m^2) or a total of 72,000 lb. (320 kN) for *each* walkway. By mere chance a videotape of the tea dance competition was being made on that memorable day, and it showed that there were sixty-three people on the two walkways, mostly concentrated on the south half and east side of the second-floor walkway, from which they had a better view of the band and the dance contestants. The actual live load, 9,450 lb.* (42 kN), was thus a small fraction of the live load required by the code.

Pfrang and Marshall realized immediately that the weak elements in the chain of structural elements were the box beams of the fourth floor. But since the stress analysis of the complex beams could not be accurately obtained by theoretical calculations, they tested in the laboratory both brand-new duplicates of the box beams and some of the undamaged actual box beams. They also computed *and* tested the ultimate strength of the hanger rods. They could thus *prove* the real cause of the walkway collapse.

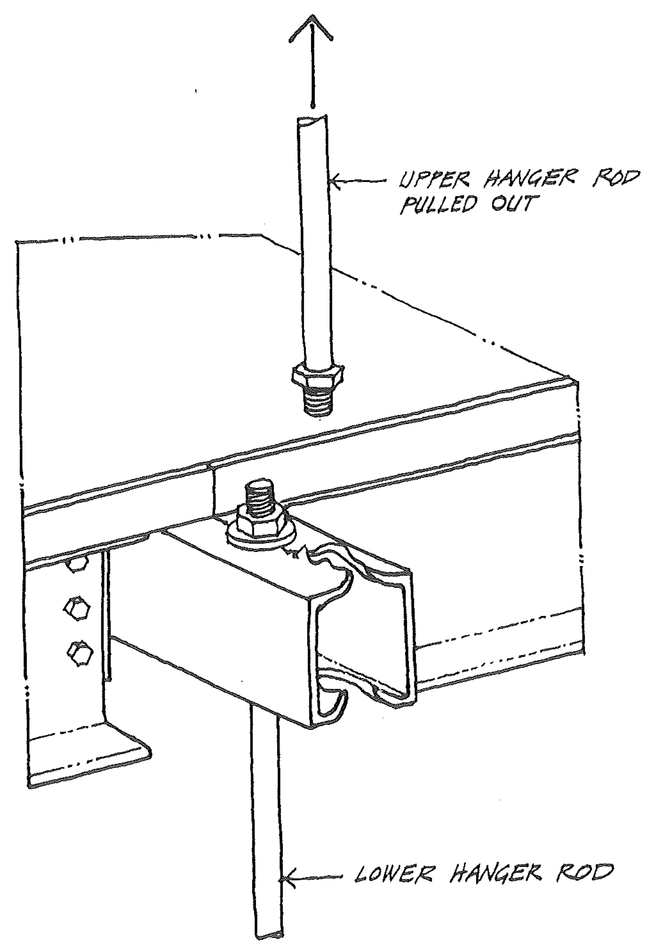
The six upper hanger rods, carrying the load of the walkways and thus supporting 24,000 lb. (107 kN) each, pulled up on the thin lower flanges of the fourth-floor box beams through a single nut and bolt connection. Under this load (*twice* the design load), the bolt first bent the lower flange of the box beams, then broke through the lower hole in it, pulled out of the hole in the upper flange, and became disconnected from the box beam (Fig. 15.5). This first happened at the midspan upper hanger rod; the remaining upper rods, incapable of taking over the load unsupported by the failed rod, pulled out of their holes, and both walkways fell down. The walkway system not only was underdesigned but also lacked redundancy (see p. 55), a most prudent reserve of strength

* 63 people @ 150 lb. each = 9,450 lb.

in structures in public places. The dangerous suggestion of the contractor, aimed at simplifying the construction of the walkways, was fatal because it went unnoticed by the design engineers.

We can do no better than report in abbreviated form the conclusions of the National Bureau of Standards report:

1. The walkways collapsed under loads *substantially less* than those specified by the Kansas City Building Code.
2. All the fourth-floor box beam-hanger connections were candidates for initiation of walkway collapse.
3. The box beam-hanger rod connections, the fourth-floor-to-



15.5 Pulled-Out Rod at Fourth-Floor Box Beam

ceiling hanger rods, and the third-floor-walkway hanger rods did not satisfy the design provisions of the Kansas City Building Code.

4. The box beam-hanger to rods connections under the original hanger rod detail (continuous rod) would not have satisfied the Kansas City Building Code.

5. Neither the quality of workmanship nor the materials used in the walkway system played a significant role in initiating the collapse.

The National Bureau of Standards report adds: "The ultimate capacity actually available using the original connection detail would have been approximately 60% of that expected of a connection designed in accordance with the specifications of the Kansas City Code." Since 60% = 0.60 is equal to 1 / 1.67, and 1.67 is an average coefficient of safety for steel structures, the above statement is equivalent to saying that under the *original* engineering design of the connections, which did *not* satisfy the code, the walkways *might not have collapsed* under the actual loads on them on July 17, 1981.

Who is to blame for the tragedy? The Missouri licensing board and the Missouri Court of Appeals found fault with the design engineers because they did not notice the essential difference between their original design and the design suggested by the contractor that they acknowledged reviewing. The National Bureau of Standards made it clear that even the original walkway design did not satisfy the Kansas City Building Code provisions but also stated, although indirectly, that the original design might not have caused a collapse under the minor live load present on the fatal day. From a human point of view, the original design, although illegal, might have avoided the tragedy.

Legally the principal and the project manager of the structural firm responsible for the design had their Missouri engineer's licenses revoked. The attorney who represented the state licensing board, Patrick McLarney, added, "It wasn't a matter of doing something wrong, they just never did it at all. Nobody ever did any calculations to figure out whether or not the particular connection that held the skywalks up would work. It got built without anybody ever figuring out if it would be strong enough. It just slipped through the cracks."

16

The Politics of Destruction

> To every thing there is a season,
> and a time to every purpose under the heaven.
>
> Ecclesiastes 3:1

We build structures with the faith that they will last forever. As we have seen in the previous sections, the forces of nature and human error often conspire to confound our optimism and cause structural failures. But there are causes yet to be explored arising from the pressure of population growth, our lack of respect for the past, or our belief that violence solves some problems. These include neglect, abandonment, replacement, and war.

The Growth of Cities

The pressure of an ever-increasing population squeezes inward on our cities, giving rise to higher and higher buildings. (Since 1850 there has been an explosive fivefold increase in the world's population to 5.3 billion.) As the land in the generally limited area of our central cities becomes more valuable, yesterday's low-rise