Avoiding Disproportionate Collapse of Tall Buildings

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Summary

Accidental circumstances must not result in disproportionate collapse. Strategies for achieving this goal are studied and corresponding design concepts are developed. The focus is on large and slender buildings with a high degree of significance and exposure. The study is based on an examination, one by one, of five general approaches: nonstructural protective measures, specific local resistance, alternative paths, isolation of collapsing sections, and prescriptive design rules. Departing from the specific-local-resistance approach, an arrangement of independent primary and secondary load transfer systems is arrived at where the primary system consists of a compact reinforced-concrete tube forming the vertical spine of the building. Based on the isolation approach, a vertical segmentation accomplished by strengthened floor slabs is suggested where a commencing pancake-type collapse is arrested by dissipating energy in shock-absorbing devices. The two design concepts maximize the tolerable accidental circumstances. The alternative-paths approach can be used for secondary systems or when a set of limited accidental actions is agreed upon.

Keywords: high-rise building; accidental circumstances; local failure; progressive collapse; design; concepts.

Introduction

The Federal Emergency Management Agency (FEMA) report on the collapse of the World Trade Center (WTC) towers\(^1\) concludes with a call for studies to determine “whether there are feasible design and construction features that would permit such buildings to arrest or limit a collapse, once it began.” An attempt is made here to answer this call. The phenomena to be dealt with are accidental circumstances (i.e. low-probability and unforeseeable events), local failure, and disproportionate collapse.

A structure that is insensitive to accidental circumstances is called collapse resistant; a structure that is insensitive to local failure is called robust.\(^2\) Insensitive means that no disproportionate collapse results from the accidental circumstances or the local failure. The terms disproportionate, accidental circumstances and local failure referred to in these definitions of collapse resistance and robustness are specified and quantified by the design objectives that must be agreed upon, as far as possible, as part of the design criteria.\(^3\) Structural features that limit the extent of a commencing collapse increase the robustness of the structure. This in turn leads to collapse resistance which is the actual design goal. Instead of increasing the robustness, a structure can possibly be made collapse resistant by reducing the probability of an initial local failure.

From each of these two main approaches, two design methods are derived. If collapse resistance is to be achieved by preventing initial local failure, the key elements, that is those elements whose failure causes disproportionate collapse, could be provided with an increased level of safety – either through nonstructural protective measures or by specific local resistance. Achieving collapse resistance through robustness, on the other hand, calls for presuming initial local failure in the design process and limiting the ensuing collapse to an acceptable extent. One method for achieving the latter is to provide alternative paths for the forces normally transmitted by the failing elements. Another approach to limiting collapse is to isolate collapsing sections by structural segmentation, which could mean a selective elimination of continuity. In addition to these direct (i.e. performance-based) methods, indirect methods in the form of prescriptive design rules can possibly be used.

These design methods are further described and discussed in Refs.\([2\) and \[3\]. In the present report, conclusions from that discussion are drawn with regard to tall buildings focusing on structures with a large height-to-width ratio, a number of stories of, say, 30 or more, and a high degree of significance and exposure (as defined in Ref.\([2]\)). Furthermore, it is assumed that the design criteria call for anticipating substantial accidental circumstances or major local failure as detailed later in this report. The objective, at this stage, is to identify design alternatives that reduce the risk of disproportionate collapse as much as possible – even if they seem unusual or are more costly in comparison with present practice. Each of the five design methods described above is evaluated in a separate section concerning its potential to provide for a collapse-resistant load transfer system. Systems that result from the respective design method are suggested where possible. It should be noted that the study is not limited to specific accidental circumstances and its results are intended to apply to all kinds of events, including fire, that possibly lead to a major local failure that induces a collapse.

Nonstructural Protective Measures

Nonstructural protective measures that provide an increased level of local safety include barriers to protect against vehicle impact or bomb blast, control of public access, fire protection, and other measures like aerial surveillance or antiaircraft systems. In that the structure must be protected from both the outside and the inside, a combination of such measures would be required. Relying on antiaircraft systems might not find enduring favor with those who are being protected in this way. Control of public access impairs the serviceability and the cost-benefit...
ratio of the building. A large amount of explosives could be smuggled into the building in small quantities over an extended period of time. Trying to counter such a tactic by scrutinizing every person entering the building every day would cause the activities the building is intended for to grind to a halt. It is thus concluded that non-structural protective measures, even if they are used in a complementary way, are unsuitable as stand-alone methods to impart collapse resistance to large permanent civilian structures such as the ones considered here. The particular role of fire protection and fire fighting is addressed in a separate section below.

**Specific Local Resistance**

If an increased level of local safety is to be provided by specific local resistance in the key elements, these elements have to be identified first. This can be done in an analytical process in which an initial local failure is modeled and the stability of the remaining structure is checked for. The extent of the initially failing part of the structure depends on the triggering accidental circumstances. In case the accidental circumstances are well defined by the design criteria, for example a gas explosion in a residential building, then the accidental action, assessed from the accidental circumstances, is also relatively well defined. The structural parts to be modeled as failed are determined on that basis. If it turns out that the remaining structure remains stable, those parts do not qualify as key elements and they do not warrant specific local resistance. If the remaining structure proves unstable, the key elements would be designed for the accidental action.

On the other hand, it might be difficult to agree upon the assumable nature and extent of accidental circumstances for structures of high significance and high exposure to malicious action or other hazards. The initial local failure must then be chosen as large as reasonably possible. For a tall building, this means the structure should be assumed to fail over the entirety of at least one story. This assumption is not too pessimistic as underpinned by the collapse of the WTC towers.\(^1\,2\) When the failure of the vertical load-bearing elements of one entire story occurs, the upper part of the building moves downward and accumulates kinetic energy. The impact forces caused by the upper part of the building striking the remaining structure below will likely exceed the reserve capacity of the structure and the collapse progresses. The structural part modeled as failed, that is the vertical load-bearing elements of one entire story, thus qualifies as a key element. This conclusion holds for all stories (except for the uppermost ones whose failure can be shown to not generate intolerable impact forces). All these key elements are contiguous. It follows that the primary load transfer system for vertical and horizontal loads must be provided with specific local resistance over almost the entire height of the structure. The question of how much specific local resistance is required remains unanswered as long as no agreement on the accidental circumstances is reached. It is maintained, though, that the tolerable accidental actions resulting from this approach are comparatively large.

With this requirement on the primary load transfer system, and considering conceivable actions (accidental or premeditated explosion, aircraft and vehicle impact, missile impact and blast, fire), it is concluded that the structural elements composing that system should be as compact as possible. The area of attack is thereby reduced to a minimum and the resistance against local action is increased to a maximum. The design concept described in the following subsections results from opting to provide specific local resistance to the primary load transfer system and the ensuing demand for compactness of that system. For the other parts of the structure (secondary load transfer system, building envelope), the consideration is not limited to the specific-local-resistance approach.

**Primary Load Transfer System**

The primary load transfer system is envisaged as a massive tube forming the vertical spine of the building (Fig. 1). Because it is assigned the entire vertical and horizontal load transfer, the tube must be somewhat larger in its outer dimensions than the core of a core and outrigger system. To maximize its compactness, the tube should have as few openings as possible and, therefore, it should not be placed at the outer perimeter of the building. The tube features a substantial wall thickness on the order of 1 m or more to increase the resistance against local action. It consists of high-strength reinforced concrete or of steel shapes embedded in reinforced concrete. Openings are limited to those required to allow access from the vertical lines of traffic and supply (lifts, staircases, ducts) placed inside the tube to the floor space on the outside, and they are staggered between consecutive stories. To prevent the incremental deposition of large amounts of explosives over an extended period of time, both the inside and the outside facing of the tube should constantly remain accessible for inspection or open to the public altogether. An explosion inside the tube caused accidently or by smaller
amounts of explosives brought into the building shortly before ignition could lead to substantial pressure build-up within the confined space inside the tube – a loading the tube should be designed for. This can be facilitated by choosing an annular cross section (Fig. 2) and by providing sufficient circumferential mild and prestressed reinforcement. The pressure build-up can be reduced by permitting venting through the access openings and by providing additional vents at the top and base of the building.

The design features just outlined result from the specific-local-resistance approach supplemented by nonstructural protective measures. Collapse resistance is achieved by preventing initial local failure. It is of interest to note that the resulting solid structure, when compared to nonsolid column-beam structures, is also more robust, that is less sensitive to local failure. This is due to its reduced degree of structuredness – a collapse-promoting feature discussed in Ref. [5].

**Secondary Load Transfer System**

The primary system suggested above is and should be autonomous regarding the global load transfer. It is the sole supporting structure for any additional structural and nonstructural components. The secondary load transfer system is therefore conceived as floors cantilevering out from the tube or spanning between its inner faces (Fig. 3). The current practice of floor design using beams and/or slabs is, in principle, suitable. However, a disproportionate collapse of the secondary system, that is a pancake-type progressive collapse of floors, is still possible and must be prevented. Because of the independence of the primary from the secondary system, the entire canon of design methods can be independently considered. Nonstructural protective measures seem unsuitable for the same reason as for the primary system. Specific local resistance is more difficult to provide, compared to the primary system, because the elements of the secondary system are intended for local load transfer and, therefore, have smaller cross-sectional dimensions. An increase in dimensions to provide sufficient resistance against local action would in all likelihood be impracticable. It is therefore better to presume local failure and to limit the ensuing collapse of the secondary system to an acceptable extent.

This can be accomplished by transferring the load of failing floors to the floors below in a capacity design approach, thus providing alternative paths. A two-step design approach is suggested. First, the elastic and plastic energy required to bend a floor down until its tip touches the floor below (Fig. 4(a)) must be more than the weight of the floor above, including a reduced live load allowance, times the vertical distance of the floors times a factor of 1.5 (to include the potential energy of the bent floor itself). Second, the rotational ductility capacity in the plastic hinge regions must be sufficient to allow for such a deformation. Progressive collapse initiated by the fall and impact of one floor is thus prevented. Numerical studies show that the required rotational ductility is difficult to be achieved with reinforced concrete beams but that it is attainable with haunched steel girders.

Analysis can be refined by assuming more than one falling floor, by increasing the weight of the falling floors by the weight of a possibly incoming aircraft, and by considering larger
degrees of deformation when establishing the available elastic and plastic energy. The impact of two floors above, for instance, could be allowed to affect two consecutive floors below (Fig. 4(b)). A refined analysis should consider the interaction between bending moment and axial force in the plastic hinge region. An incoming aircraft, resulting in a concentrated additional load, would require sufficient circumferential load distribution capacity. This can be provided by perimeter beams working in bending and, if necessary, capable of catenary action. The design approach described here applies to the cantilever floors. A similar capacity design approach can be developed for the floors spanning between the inner faces of the tube.

An alternative and contrary approach to limiting the collapse of the secondary system to an acceptable extent is to isolate collapsing sections through structural segmentation. In continuous girder bridges, isolation can be achieved by inserting hinges that eliminate continuity at selected locations. This idea applied to the cantilever floors of the secondary load transfer system considered here entails the insertion of joints running perpendicular to the core to divide the floor space into a number of structurally independent cantilever floor segments (Fig. 5). The joints of all floors are vertically aligned, that is placed at the same locations in plan. If one floor segment fails and falls, the ensuing collapse would be limited to the floor segments directly below the failed segment (similar to the Ronan Point failure). Compared to the alternative-paths approach discussed above, the maximum possible damage here seems larger. Both approaches can be combined: If in a design according to the alternative-paths approach circumferential load distribution is eliminated through the insertion of joints, the energy balance established for the design of the cantilever floors does not have to include the concentrated additional aircraft load. The isolation of a collapse within the secondary system can also be achieved through vertical segmentation accomplished by “strong floors” that serve as horizontal segment borders (instead of the horizontal segmentation brought about by vertically aligned joints). An application of this approach to the overall structural system is discussed in a later section.

**Building Envelope**

In addition to the primary and secondary load transfer systems, the building envelope (façade) requires attention. Windows, cladding panels, and other envelope elements can be mounted either directly or by means of light framing on the cantilever floors. If the corresponding weight is considered in the design of the secondary load transfer system, following the alternative-paths approach suggested in the previous subsection, the building envelope will not enter into a collapse progression on its own. Appropriate measures should be taken so that the assumed downward bending of one floor to the floor below does not transmit excessive forces through the façade to that floor. This can be done by choosing a vertically overlapping or staggered arrangement of façade elements or by applying the force associated with vertically crushing the façade as a quasi-static load, including a dynamic magnification factor, in the elastic design of the cantilever floors. Alternatively, the building envelope is designed as a self-supporting structure. Its collapse resistance can be achieved by providing alternative paths or by isolating collapsing sections through the insertion of vertically aligned joints. The provision of alternative paths, for example by designing a frame system with stiff horizontal spandrel beams, has the advantage of a presumably smaller extent of damage. In either case, a self-supporting structure must be structurally connected to the cantilever floors for wind load transfer and out-of-plane stability of the columns. This entails the risks (or benefits) of interaction between that structure and the secondary load transfer system. If the interaction proves or is suspected to be detrimental to the collapse resistance of the secondary system, then the connections between building envelope structure and floors should be designed as structural fuses that release at a defined force.

In case a suitable decoupling mechanism is not provided, the envelope structure becomes part of a more complex secondary load transfer system in which the floors do not work in cantilever action but in beam action. The design approaches for the floors and the envelope structure can be based on the provision of alternative paths, on the insertion of vertically aligned joints or on a combination of both methods. Alternatively, the “strong floor” concept introduced in the previous subsection can be used and combined with any kind of envelope structure.

The response of such combined systems to scenarios of collapse onset is more difficult to assess than a secondary system relying solely on cantilever action. A combined secondary load transfer system consisting of floors and envelope structure is considered whose design is based on the alternative-paths approach. According to the premise introduced above, the envelope structure must then be designed for the forces induced by the fall and impact of one or more floors, including a part of the envelope structure plus aircraft debris, on the floor below (Fig. 6). In case the initial failure is widespread in circumferential direction, no alternative paths within the envelope structure can form: The impact forces act on a nonredundant structure, like a column in axial compression, and must be taken elastically. The floor design, on the other hand, benefits by a larger number of plastic hinges thus requiring less ductility capacity per hinge. The floors above the failing floors lose their perimeter support from the envelope structure. They should thus be able to transmit the contributory self weight and live load, as well as the dynamic loading from the sudden removal of the outer support, in cantilever action. Alternatively, the

**Fig. 5: Segmentation of secondary load transfer system by joints**

**Fig. 6: Assumed damage and admissible deformation in combined secondary load transfer system**
envelope structure above the zone of failure is used to support these floors – a load path that developed in the WTC towers.\textsuperscript{1,4} The affected columns are converted from compression members to hanger-type tension members. The further load transfer to the primary system is provided by the combined cantilever action of the floors above or through outrigger trusses at the top of the building.

**Overall Structure**

The design alternatives discussed in this section flow from the choice to ensure collapse resistance by providing specific local resistance to the key elements of the global load transfer. Contrary to the other design strategies discussed in the subsequent sections, a hierarchical arrangement of largely independent primary, secondary, and possibly tertiary load transfer systems results from that choice. Placing the tube of the primary system inside the perimeter of the building has advantages additional to those stated above: The tube is less exposed to external forces from blast or impact because the building envelope and the floor structure between envelope and tube mitigate and distribute such a loading.\textsuperscript{5} This benefit results from energy dissipation and fragmentation of incoming projectiles or aircrafts. Another advantage of such a system, particularly when combined with a non-self-supporting façade, is greater architectural freedom in the design of and subsequent modification to the building envelope.

**Alternative Paths**

This approach aims at providing alternative paths for the forces normally transmitted by failing structural elements (redundancy). The focus is on the elements identified as key elements, that is those elements whose failure, if no further action is taken, causes disproportionate collapse. For tall buildings, it was argued above that the entirety of the vertical load-bearing elements of any one story qualifies as a key element if no agreement upon the nature and extent of accidental circumstances can be reached. It is concluded that, in such a case, no alternative paths can be provided for the global load transfer. The underlying assumption “failure of an entire story” to the radical conclusion “no alternative paths available” is corroborated by experience and does not seem farfetched. If it is argued that much has been learned from the collapse of the WTC towers and that for future designs such an assumption is excessive due to improvements in structural design and fire protection, then such arguments actually refer to the safety against initial local failure and the specific local resistance of the structure and not to its robustness. It should be added that the lessons learnt from 11 September 2001, even if useful, relate to the circumstances and actions of a single event in the past. The future is unknown.

If, however, an applicable set of limited accidental circumstances is agreed upon, the designer can take a less radical view. In case the failure of an entire story is ruled out based on a careful study of conceivable accidental actions and proper design, then alternative paths could remain available. Further analysis and design would then be based on the amount and location of the initial local damage as inferred from that study. Following such an approach, it seems that any structural system currently in use for tall buildings, such as frame, shear wall, core and outrigger, or tubular systems, could lend itself to providing viable alternative paths. The redundancy of core and outrigger systems was demonstrated in the pre-collapse response of the WTC towers.\textsuperscript{1,4} Identifying those structural systems that are particularly suitable for providing alternative paths needs further study. It is anticipated that, in order to prevent the failure of an entire story, this approach would need to be applied in combination with the specific-local-resistance approach.

**Isolation of Collapsing Sections**

Another possibility for limiting collapse induced by local failure is to isolate collapsing sections through structural segmentation. Such an approach seems most suitable for horizontally aligned structures, like continuous girder bridges, where the collapse progression in longitudinal direction is arrested at certain locations and isolation is safely and easily achieved by a well thought-out insertion of hinges.\textsuperscript{5,7}

**Horizontal Segmentation**

As discussed above, a similar approach, with linear joints instead of hinges, can be used for the secondary load transfer system of a building. When this idea is applied to the overall structure, a horizontal segmentation, achieved by vertically aligned joints, is introduced to the effect that if one segment fails, the ensuing collapse is limited to the segments below. There would be no collapse progression in the horizontal direction. To keep the possible extent of damage reasonably small, the segments should be small and many. For this reason, a horizontal segmentation of the global load transfer system through the insertion of joints is less appropriate for tall buildings. With the exception of buildings with small height-to-width ratios (which are not the focus of this report), the segments would become too small to be self-supporting. Designing the joints so that the horizontal cross-boundary interaction needed for stability and the transfer of horizontal loads is not impaired is difficult. Furthermore, the tolerable accidental actions decrease with the segment size, which again invokes the problem of agreeing on a set of applicable accidental circumstances.

On the other hand, the smaller the height-to-width ratio of a building, the more appropriate horizontal segmentation becomes. Horizontal segmentation through expansion joints apparently helped to limit damage to the Pentagon Building on 11 September 2001.\textsuperscript{1,9} Instead of by inserting joints, horizontal segmentation in a building with small height-to-width ratio can also be achieved through segment borders sufficiently strong to withstand the forces induced by the collapse of an adjacent section.\textsuperscript{3} While this alternative is not pursued further here, it opens up an interesting line of thought when combined with the idea of using vertical instead of horizontal segmentation.

**Vertical Segmentation**

The collapse of the WTC towers progressed in vertical direction. If there were horizontal lines of defense, the collapse might have come to a halt. A design idea based on this observation is to isolate collapsing sections through vertical segmentation. In this case, only a strengthening of segment borders, and not the insertion of joints, is a viable method for isolating a collapse. The applicability of this approach is not limited to particular structural systems within a segment. It is further developed and gradually refined in the following paragraphs.

The height of one segment is first assumed to be a certain fraction, say, one tenth, of the building height. Each
segment comprises the entire floor area and is limited by two horizontal segment borders which likewise extend over the entire floor (except the uppermost segment which is limited by one such border at its bottom). In case the vertical load-bearing elements of one or more contiguous floors fail, two failure fronts will propagate vertically— one downward and the other upward—from the point of initial failure to the two adjacent segment borders. At the same time, the upper part of the building (the part above the failing segment) moves downward as a rigid body. The rotational motion component is small (a preliminary assumption suggested by the collapses of WTC 1 and 7 that deserves further consideration; see also Ref. [10]). During the fall of the upper part of the building, the border below the failing segment is already being loaded by the impacting debris of the failed floors above it. The main impact occurs when the upper part of the building strikes the accumulated debris on the lower segment border. Both the upper and lower parts of the building are assumed to be intact until then. Large impact and gravitational forces result.

The segment borders must be strong and stiff enough to withstand and distribute such forces. As the points of load application are unknown but an efficient load distribution must nevertheless be achieved, they are envisaged as massive reinforced or prestressed concrete slabs of substantial thickness (on the order of 0.40 m). They are preferably made of fiber-reinforced high-strength light-weight concrete to reduce weight which otherwise would increase the impact forces. Openings in the slabs should be limited to the minimum required for the vertical lines of traffic and supply. Even if the segment borders withstand the impact forces and achieve a good load distribution, the internal forces within the structure above and below the failing segment are likely beyond the level which can reasonably be designed for. A further difficulty is that the magnitude of the design impact forces is difficult to establish.

These problems are overcome by the introduction of shock-absorbing zones within the segment borders (Figs. 7 and 8). Instead of one massive slab, two such slabs placed at a vertical distance of one-story height or less are provided. The two slabs are connected by structural elements designed to bear the forces from the ordinary (i.e. noncollapse) design loads. A further requirement is that these elements give way before the structure above or below does when the two-slab segment borders of a failing segment come under vertical compression due to impact forces. Moreover, these elements and additional shock-absorbing devices placed between the two slabs are designed in such a way that a large amount of energy is dissipated in a calculable way when the two slabs move against each other in vertical direction. To reduce the impact forces to a minimum, the relative vertical displacement between the two slabs should be smooth and approach the clear spacing between them; the energy to be dissipated during that displacement corresponds to the kinetic energy of the mass impacting from above.

The shock-absorbing devices must be designed to fulfill such requirements. They are preferably placed around the columns or close to walls (Fig. 8). They could consist of telescoping large-diameter steel tube segments filled with a material that allows high volumetric compressive strain going along with large plastic and/or fracture energy (Fig. 9). Candidates for such material are scrap metal and porous tuff gravel. Metal honeycomb structures are suggested in Ref. [11] for similar purposes. Numerical studies show that such devices can be designed and the underlying concept thus seems feasible for buildings as large as the WTC towers.6 The available space in between the two slabs of a segment border can be used like ordinary floor space or it could house machinery or serve as storage area.

It is of interest to note that such a design reveals a third possibility of achieving segmentation and collapse isolation. Instead of creating a segment border by accommodating large displacements (by reducing continuity) or large forces (through strengthening), a segment border can also be established by providing a high capacity of energy dissipation. This is a combination of the former two approaches as it involves displacements and forces at the same time.

Concerning the analysis of such impact and shock-absorbing scenarios, it is noted that the destruction of the failing segment itself consumes energy. Its magnitude can be estimated from the observed vertical acceleration of building collapses. The more that acceleration falls short of the acceleration of free fall, the more energy is consumed by the destruction of the building. Because the pressure waves travel much faster than the failure fronts, the elements connecting the two slabs of the adjacent (and also of remote) segment borders could fail and their shock-absorbing devices could respond almost instantaneously. This would have a reducing effect on the collapse
progression, which could already come to a halt within the failing section.

In the design concept indicated in Fig. 7, each segment comprises a number of stories and is relatively large. The extent of material and immaterial damage corresponds to one segment and, therefore, is equally large. Minimizing the segment size, and the extent of damage, leads to a further design alternative in which each segment consists of just one story. Each floor must then be designed as a segment border, that is as one massive slab. Because the failing segment is smaller, the floor slabs can be of less substantial thickness (say, on the order of 0.25 m). On the other hand, shock-absorbing devices must be provided in each story. Due to the reduced falling height, however, the kinetic energy is also smaller, to the effect that the overall requirement of shock-absorbing devices is not much more than before. This also applies to the reduction of usable floor space caused by the devices.

The latter alternative thus achieves a reduced extent of damage at about the same or only slightly higher cost and, therefore, seems preferable. A further advantage is that, due to the reduced falling height, there is less time for tilting and less uncertainty concerning the actual structural response. A similar design concept and supporting numerical studies are presented in Ref. [11]. Observational indications that, in principle, it is possible to arrest a commencing collapse are mid-story building failures without ensuing pancake-type collapse such as those that occurred during the 1995 Kobe earthquake. It is noted that vertical segmentation is the only design approach that does not impose limits on the tolerable accidental circumstances – at least not in horizontal direction.

Prescriptive Design Rules

The prescriptive design rules suggested in the literature and implemented in some building codes aim at tying together main structural elements, enabling catenary action, and providing ductility. It is thereby attempted to ensure collapse resistance through a general increase of continuity and alternative paths. An application to the global load transfer system of tall buildings and other major structures seems questionable for two reasons. Such structures experience large internal forces and a high degree of structural interaction that is difficult to generalize. Prescriptive design rules, therefore, may increase the quantity but not necessarily the quality of alternative paths. If alternative paths are not provided with the strength required to withstand the forces transmitted by continuity, they may become overloaded and not prevent but rather promote collapse progression. The force transfer should thus be checked down to the foundation; forces should be determined based on the overstrength of elements introduced for continuity. In other words, a performance-based approach should be used when the collapse resistance of the global load transfer system is based on the provision of alternative paths. The dependency of the efficiency of such measures on the extent of the initially failing part of the structure will only then become apparent.

But safety is not the only characteristic that might be impaired when using prescriptive design rules. Tall buildings are unique and expensive structures. Thus, for the sake of economy, it is worthwhile to spend effort on accurate analysis and custom-made design, that is, to use a performance-based approach for the design of the global load transfer system. In the case of small- to medium-sized structures, on the other hand, that kind of commitment may become disproportionate. At the same time, the consequences of a failure are less severe. Prescriptive design rules might thus be preferable for such structures. Another field of application could be the design of secondary elements of tall buildings, in particular for enabling catenary action to prevent impact forces from falling components, provided the primary load transfer is not unduly affected by such measures.

Fire Protection, Fire Fighting and Evacuation

Whatever strategy is followed for structural design, thought must be given to nonstructural protective measures for fire protection and fire fighting. In addition, rapid and safe egress from the building must be assured. The measures taken for these purposes, both in terms of physical provisions and emergency procedures, must not only be efficient but also robust, which means that they remain operable in the case of local damage or partial collapse. Fire fighting in tall buildings usually depends on water that is pumped up from ground level through standpipes and supplied by hoses. Even if complemented by secondary supply from water tanks within the building, the automatic and manual fire fighting capabilities of such a system might eventually become inoperable through the same event that ignites the fire. Such more conventional fire fighting systems seem best in line with the design approach outlined in section “Specific Local Resistance” above: Standpipes are fed through the massive tube forming the primary load transfer system, which means they are relatively well protected against physical damage. The same holds for the staircases. Accidental circumstances inside the tube which leave the structure intact could still affect the standpipes or staircases. To create redundancy for fire fighting and evacuation, the primary system tube should therefore be partitioned through vertical inner walls. Each compartment created in this way would house independent standpipes and staircases.

For general structural systems, it seems necessary to develop new fire fighting systems in order to raise their robustness to an appropriate level. Instead of water, other fire extinguishing agents such as carbon dioxide or foam can be used. The constituents are relatively light and need little energy and only light equipment for discharging them. They can be distributed in a decentralized manner over the entire building to the effect of creating autonomous and redundant systems that are independent of external energy supply and the proper functioning of standpipe systems.
Finally, alternative evacuation methods should be developed. Helicopter rescue from the roof might become more of a viable option if special equipment (e.g., multiple-person rescue baskets) is developed and procedures are improved. For special structures, such as towers and special manufacturing environments, controlled descent devices are permitted by the Life Safety Code to provide escape routes. Occupants could also be evacuated to neighboring buildings by zip lines and breeches buoys as it has been practiced for the rescue of sailors from ships.

**Conclusion**

A structure is called collapse resistant if accidental circumstances do not cause disproportionate collapse. Strategies for creating collapse-resistant tall buildings are studied. The focus is on structures with a large height-to-width ratio, a large number of stories, and a high degree of significance and exposure for which the occurrence of substantial accidental circumstances or major local failure must be assumed. The objective is to reduce the risk of disproportionate collapse as much as possible even if the resulting measures seem unusual or uneconomical in comparison with present practice.

The study is based on an application of various approaches. Two avenues can be taken, each branching into two methods. Each of these four methods – nonstructural protective measures, specific local resistance, alternative paths, and isolation of collapsing sections – are examined and, if found feasible, corresponding design concepts for tall buildings are developed. In addition to these direct methods, indirect methods in the form of prescriptive design rules are discussed.

**Nonstructural protective measures** that are based on controlling public access and the structure's environment can be used in a complementary way but are found to be unsuitable to serve as stand-alone methods to impart collapse resistance to the kind of structures discussed here. On the other hand, and irrespective of the strategy followed for structural design, improved measures for fire protection, fire fighting and evacuation must be developed. These measures should not only be efficient but also robust in the sense that they remain operable in the case of local damage or partial collapse. A few suggestions are made to this effect.

If collapse resistance shall be provided by specific local resistance, the accidental circumstances to be considered in the choice and the design of key elements must be agreed upon as a design objective. Such an agreement is difficult to reach for the kind of structures considered here – very large tall buildings with a high degree of significance and exposure. It is thus argued that, in such a case, the key elements must be chosen as large and strengthened as much as reasonably possible in order to maximize the tolerable accidental circumstances. These and further considerations lead to a design concept with a hierarchical arrangement of largely independent primary, secondary, and tertiary load transfer systems. The primary system is a key element, and thus has to be provided with specific local resistance, over almost its entirety. It is envisaged as a compact reinforced-concrete tube of substantial wall thickness forming the vertical spine of the building. The secondary system is suggested as floors cantilevering out from the tube and spanning between its inner faces. A progressive collapse of this secondary system must likewise be prevented. Because of the independence of the primary from the secondary system, the entire canon of design methods can be considered. The most feasible approach is the provision of alternative paths involving the plastic reserves in bending of the floor structure. Alternatively, a commencing collapse of the secondary system can be arrested by isolating the collapsing section. This is accomplished either by vertically aligned joints, which bring about a horizontal segmentation, or through "strong floors," which serve as horizontal borders within a vertical segmentation. The building envelope can be designed as a nonstructural tertiary element supported by the secondary system, as a self-supporting system, or as a part of a modified secondary system. The structural system suggested here tolerates large accidental circumstances and, in this respect, is second only to a design based on vertical segmentation.

The third design method – alternative paths – aims at limiting a collapse once it begins. Instead of the accidental circumstances, the design objective to be agreed upon is now the assumed extent of the initial local failure. Again, it is argued that such an agreement is difficult to reach for the kind of structures considered here and that the initial local failure must be chosen as large as reasonably possible. When invoking the possibility of complete failure of one entire story, it is found that no alternative paths are available for the global load transfer system. When adopting a less radical view, by effectively combining the specific-local-resistance and alternative-paths approaches, it seems that any structural system currently in use lends itself to providing viable alternative paths. Identifying those structural systems that are particularly suitable for this purpose needs further study.

A commencing collapse can also be limited through an isolation of collapsing sections. This is accomplished by a horizontal segmentation with vertical segment borders or by a vertical segmentation with horizontal segment borders. In the first case, segmentation is achieved by inserting vertically aligned joints or, conversely, by strengthening the segment borders. These approaches are appropriate for buildings with small height-to-width ratio but not for the kind of structures considered here. In the second case, only a strengthening of segment borders, combined with the introduction of shock-absorbing energy-dissipating zones, is a viable method of segmentation. Various design alternatives are discussed. In the most promising one, the segment size is minimized to the effect that each story constitutes one segment, each floor slab is designed as a segment border, and shock-absorbing devices are provided in each story. Various kinds of shock-absorbing devices are outlined. Although the least conventional approach, there are numerical and observational indications that vertical segmentation is suitable for arresting collapse in tall buildings. Compared to the other methods studied in this report, it imposes the least limitation on tolerable accidental circumstances.

Prescriptive design rules might be appropriate for small- to medium-sized structures. Their applicability to the kind of structures considered here is limited. Tall buildings experience large internal forces and a high degree of structural interaction that is difficult to generalize. Even if the quantity of alternative paths is increased by prescriptive design, this does not always mean an increase in quality, and collapse progression may not be prevented but promoted. Contrary to alternative paths provided through direct design, the dependency of the efficiency of such measures on the extent of the initially failing part.
of the structure does not become apparent. Furthermore, tall buildings are unique and expensive structures so that it is more economical to spend effort on accurate analysis and custom-made design, that is, to use a performance-based approach instead of prescriptive design rules. If prescriptive design is used for secondary elements of tall buildings, it must be ensured that the collapse resistance of the primary load transfer system is not impaired by such measures.

References