A COMPARISON OF BLAST AND EARTHQUAKE RESISTANT DETAILING CONCEPTS ADOPTED FOR REINFORCED CONCRETE BUILDINGS

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ABSTRACT: It is the duty of the professionals involved in the building industry to ensure that the buildings are safe and healthy. However, in many instances such as blasts and earthquakes, the building industry has failed to ensure this which led to many casualties among the general public. It is shown in this paper that the present practices adopted for buildings in Sri Lanka would not be sufficient in this respect and further precautions and improvements should be taken for future buildings. The concepts that can be used at the planning stage for the structural form are highlighted. The methods available for improving the ductility of the structures with reinforcement detailing are also highlighted. The cost increases associated with such practices are presented.
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INTRODUCTION

It is the primary duty of architects and engineers to ensure that the public buildings constructed are safe and healthy. Many buildings already constructed in Sri Lanka are deficient in safety with respect to blasts and earthquakes. This paper highlights the areas which can be further improved with respect to safety in future buildings.

Blasts that result due to explosion of large vehicle bombs have become a new threat to buildings. Explosions generate shock waves that increase the pressure suddenly. Blast waves propagate at supersonic speeds until they encounter an object such as a building. The blast shock front penetrates through window and door openings into the building subjecting the floors, ceilings etc. to blast loads (Longinow & Mniszewski, 1996).

Earthquake resistant structures are not considered a necessity in countries located away from earthquake prone zones, such as Sri Lanka. However, historical records show that it may not be advisable to assume that no earthquake events will take place close to Sri Lanka (Abayakoon, 1998). Thus, adoption of some precautions will be quite beneficial in improving the safety of buildings. One of the primary aims should be to prevent the collapse of buildings due to earthquakes. This is a requirement against blasts as well.

It is shown in this paper that the precautions and strength enhancement measures that should be taken against both blast and earthquake resistance are somewhat similar. Therefore, it would be possible to enhance the safety of the buildings with few common goals that should be incorporated at the initial layout planning and detail design stages. The blast and earthquake resistant reinforcement details that can be adopted for reinforced concrete buildings are also highlighted. The cost implications of adopting desirable structural details are also presented.

OBJECTIVES OF THE STUDY

The main objectives of this study are as follows:

1. to highlight the deficiencies of the present practices adopted in buildings with respect to blasts and earthquakes,
2. to determine the means available for improving the safety of future reinforced concrete buildings with respect to structural forms selected,

3. to determine the methods available to improve the safety of proposed reinforced concrete buildings with respect to structural detailing, and

4. to determine the cost increases associated with adopting blast and earthquake resistant details for reinforced concrete structures.

**METHODOLOGY**

In order to achieve the above objectives, the following methodology was adopted:

1. A literature review was carried out to determine the desirable features that should be adopted in commercial buildings with respect to blasts and earthquakes.

2. A comparison was made for the structural forms recommended for enhanced blast and earthquake resistance to determine the ways and means of reaching compromise solutions.

3. A comparison was made with respect to the structural detailing recommended to achieve enhanced blast and earthquake resistance of reinforced concrete structures.

4. A detailed cost study was carried out to determine the implications of adopting blast and earthquake resistant detailing for reinforced concrete structures.

**BLAST RESISTING CONCEPTS**

It is relatively easy to protect the buildings from blasts that occur inside by having proper security. However, building owners have little control over blasts that occur externally close to the buildings. In this paper, attention is focused on both these types of blasts.

In order to protect people against blasts, buildings should not collapse catastrophically, they should not burn out of control and people should be protected against flying fragments (Elliot et al., 1992). The ability of structures to resist a highly impulsive blast loading depends to a considerable extent on the structural detailing adopted for slabs, beams and columns.

It is very important to enhance the ductility of the load resisting system to resist large impulsive loading. This means that the structure has to deform inelastically under extreme overload, thereby dissipating large amounts of energy prior to failure (Elliot, et al., 1992). It was found that in many explosions, ductile elements have withstood peak pressures much in excess of static strength without major loss of strength (Mainstone, 1976). The detailing concepts adopted for majority of reinforced concrete buildings constructed in Sri Lanka are based on CP 110 (1972) and BS 8110 (1985) and the Standard Methods of Detailing of Structural Concrete (The Institution of Structural Engineers, 1989). The main drawback of such detailing is that they are intended primarily to withstand static loading and hence does not provide adequate ductility to prevent disproportionate collapse of the structure or excessive damage, when subjected to dynamic loading.
The modern trend in the building industry in general is to construct highly irregular structures for aesthetic reasons. The structural designer of such buildings should be extremely careful since a well distributed lateral load resisting system is a pre-requisite against blast effects specially to prevent torsional effects (Ettouney, et al, 1996). In this respect, symmetrically arranged concrete shear wall structures or wall frame structures can be quite useful.

In addition to these measures, the location of the building is also important in minimising the blast damage. The power of explosion declines as the cube root of distance from the source to the explosion (Elliott et al, 1992). Therefore, the distance from an explosion, "stand off", has the potential to provide excellent blast protection. In practice, the access by vehicles should be kept at a distance from where people work. A stand off distance of 25 - 30 m is considered as a minimum acceptable. At this distance, the building will be exposed to relatively low pressures fairly uniformly distributed over the facade (Ettouney et al., 1996). The present practice in Sri Lanka is contrary to this recommendation where most of the buildings are constructed as towers rising close to the building line on either side of major roads. These offer very little protection to the occupants of the building from blasts that can occur on the street.

The shape of the building also should be such that it would not have any re-entrant angles on the side facing the likely attack. Such re-entrant corners can cause multiple reflections and enhance the blast wave intensity (Mays and Smith, 1995). The extensive use of glass on the facade of the building also makes it vulnerable to excessive blast damage. These undesirable features can be found in many modern buildings constructed in Sri Lanka.

Due to various architectural features or due to the nature of the terrain, buildings may be constructed at a certain height above the road. In these buildings, a wide flight of stairs is generally used in the front to provide access. The ground that rises away from the source of explosion towards a building also enhances a blast wave and hence this is not a desirable feature (Mays & Smith, 1995). Although this arrangement is not common in Sri Lanka mainly due to flat terrain in most of the major towns, such level differences should not be purposely introduced for the ground floors on the basis of aesthetics.

In modern office buildings, an atrium or a lobby area with large open spaces are often used. Thus the column grid spacing used for the ground floor can be much larger than the grid spacing used for upper floors. Therefore, there may be long span transfer girders located above the ground floor level. These transfer girders are most likely to experience the maximum effect of blast loads, since ground floor has to bear the highest intensity. Since only few columns are used with the transfer girders, there is a possibility for those columns to become key elements where the failure of such elements can lead to disproportionate collapse of a structure. When there are columns that acts as key elements, those are generally designed for a lateral load of 34 kN/m², acting on its periphery as specified in BS 8110/1 (1985), Cl 2.6. It should be noted that 34 kN/m² lateral load used for the design of key elements relates to pressures arising from an internal gas explosion. Hence, such design loads in no way provide sufficient strength to resist loads due to massive blasts (Elliott, et al., 1992). Therefore, the introduction of transfer girders for the sake of having few large spans may not be a desirable practice.
Transfer girders also may not perform very well in blast loading unless detailed to enhance the ductility (Etouney, et al., 1996). Thus, avoidance of transfer girders at the ground floor level altogether may be desirable for buildings to be constructed in future. If such large open space lobby areas are required, those could be included as an addition to the main building in front of it. In this case, this area will also be able to provide the stand-off to the main building.

EARTHQUAKE RESISTING CONCEPTS

There are two major factors that discourage the use of earthquake resistant design and detailing of reinforced concrete structures constructed in Sri Lanka. They are the belief that earthquake resistant structures will cost more than the normal structures and the misconception that Sri Lanka is located in an area where no earthquakes will occur. It was reported by Abayakoon (1998) that a total of 88 earthquakes have occurred around Sri Lanka since 1819, where the magnitudes varied from 3.0 to 6.0 on the Richter Scale. Eighteen earthquakes recorded magnitudes between 5.0 and 6.0. These 88 earthquakes have occurred within the rectangle of latitude 2°-12° north and longitude 76° to 85° east. Sri Lanka lies between 5° 55' and 9° 51' north latitude and 79° 43' and 81° 53' east longitude. These records indicate that it may not be advisable to ignore earthquakes for buildings constructed in Sri Lanka.

Buildings should be able to resist minor earthquakes without damage, moderate earthquakes without structural damage, and to resist major earthquakes without collapse (Hutchinson et al., 1995). This means that certain degree of damage is acceptable, but not the loss of life due to collapse of the structure. It is possible to detail the reinforced concrete structures to enhance the ductility so that the chances of the building collapsing would be remote. However, good reinforcement detailing alone is not sufficient to prevent the collapse of a structure, but a reasonably good structural form is also necessary. The desirable forms of the structure are discussed with respect to the shape of the structure, symmetry, distribution of strength and the failure mechanisms of beams and columns.

Effects of shape: The shape should be simple such as square, rectangular, circular, but not T, U or I shapes. The structures having minor re-entrant corners are considered as regular, but large re-entrant corners creating a crucifix form are not desirable since the response of the wings is generally different from the response of the structure as a whole.

Effects of symmetry: Even for structures not symmetrical in plan shape, it is important to arrange strong elements to prevent the twisting of the structure thus avoiding the development of torsional effects.

Effects of distribution of strength: In Sri Lanka, many clients request double height lobby areas with mezzanine floors for elegance at the ground floor level. This leads to irregular structural configuration in vertical direction and some weaker columns. In many past earthquakes like San Fernando, California, 1971, Erzincan, Turkey, 1992 (Saaticioglu & Bruneau, 1993) and Costa Rica, 1991 (Mitchel & Tinawi, 1992), Kobe, Japan, 1995 (Sanders, 1995), buildings with irregular distribution of mass and strength vertically have suffered excessive damage at such locations. In many instances, these weak columns have failed during earthquakes leading to loss of life. This happens because the normal height upper floors are much stiffer and hence tend to behave as one block. Another source of
irregularity is the introduction of large set backs in buildings. These introduce sudden changes in mass which may lead to unpredictable force distribution close to the set back in an earthquake event.

**Failure mechanisms of beams and columns:** The modern trend in buildings is to maximise the spans while minimising the number of columns. This would necessitate beams of considerable depth where the column sizes are kept relatively small. In an event of an earthquake, the strong beam remain elastic while the weak columns suffer concrete crushing or shear failure. This may lead to the collapse of the building resulting in loss of life. In Sri Lanka, this aspect is not paid much attention by architects and structural design engineers. Therefore, small columns supporting large beams is a common sight in many existing buildings.

**STRUCTURAL FORMS FOR BLAST AND EARTHQUAKE RESISTANCE**

The desirable structural forms for blast and earthquake resistance are discussed with respect to the shape of the structure, symmetricity, distribution of strength and failure mechanisms of beams and columns.

**Effects of shape:** It is desirable to use plan shapes without re-entrant corners with respect to blast resistance since such corners can amplify the blast effects. Large re-entrant corners are not desirable with respect to earthquake resistance as well since they can make the structure irregular in shape. The geometric irregularities that can be acceptable on plan for regular structures are given in AS 1170.4 : 1993. Those are shown in Figure 1. When these limits are violated, the structure may need a dynamic analysis to determine the distribution of earthquake forces. However, such an analysis is not a guarantee that the structure will have a desirable behaviour when geometric irregularities are substantial. Thus, when re-entrant corners are essential, those should be kept within the limits shown in Figure 1 and the facade in such areas should be made resistant to blast loads by using an appropriate strong material such as concrete. The number of openings in such areas also should be minimised.

**Effects of symmetry:** Irregular buildings, such as those with lateral load resisting strong elements arranged unsymmetrically, will be subjected to excessive torsional moments in large blasts and earthquakes. Therefore, even for buildings with irregular shapes in plan, every attempt should be made to ensure that the shear centre of strong elements of the building coincides with the line of action of forces.

**Effects of distribution of strength:** The use of double height lobby areas introduce soft stories in buildings. In such instances, it is advisable to introduce columns of cross section larger than usually required. Such large columns would help to reduce the deflections and also the difference in stiffness. As a result, the rotational deformations of columns also will be reduced. Such columns can also be carefully detailed to provide them with sufficient ductility, thus avoiding brittle failure of columns. The use of earthquake resistant reinforcement details in these columns can enhance the confinement to concrete thus the rotational capacity of columns also will be improved. This measure will be of help with respect to blasts as well since large reinforced concrete columns would be able to resist blast effects much better due to their massive size and reserve strength.
Another source that introduces uneven distribution of strength is set-backs. With respect to blast resistance, it is desirable to have large set-backs in order to improve the stand-off for the tower part of the building. However, this is not desirable with respect to earthquake resistance. Therefore, a compromise solution will be required for setbacks. It is recommended in AS 1170.4:1993 to have setbacks as shown in Figure 2. When such recommendations are violated, it will be necessary to carryout dynamic analysis to determine the force distributions that may arise in earthquakes. However, such an analysis may not be a guarantee of satisfactory behaviour in an earthquake. Therefore, it is desirable to comply with the guidelines given in Figure 2. When this is not possible due to functional requirements, it would be desirable to construct the projecting part of the building at ground floor level as a separate building.

**Failure mechanisms of beams and columns:** It may be advisable to avoid large span beams whenever possible with respect to earthquake resistance. Therefore, it is desirable to use smaller spans supported on large number of columns. In earthquakes, the use of detailing that improves the ductility will enhance the chances of survival of such beam column monolithic systems. In blasts also, the chances of the structure collapsing due to one or two columns being destroyed would be reduced since the upper part of the structure may now be able to behave as a very deep lattice girder. However, such a behaviour would not be possible when the number of columns are minimised by maximising the spans.

It can be seen from above that the structural form can be selected in such a way so that the resistance to blast and earthquake effects can be enhanced. Therefore, for future public buildings constructed in Sri Lanka, these features should be carefully incorporated at least to some degree.

**STRUCTURAL DETAILING FOR BLAST AND EARTHQUAKE RESISTANCE**

The use of good structural forms alone is not sufficient in minimising the casualties in blasts and earthquakes. Even monolithic structures with good structural forms can collapse due to lack of ductility. The structural detailing recommended in BS 8110 is adequate for static loading arising out of dead and live loads. However, when the structure is subjected to dynamic loading of high magnitudes, ductility offered by such detailing would be inadequate to prevent excessive damage.

**Earthquake Resistant Reinforcement Details**

It is possible to resist earthquake loads on structures by relying either on the over-strength in the structure or the ductility of the structure. Relying on over-strength means designing of structures for larger load intensities than usual so that the resulting structure will be stronger than required under normal circumstances. Relying on ductility means enhancing the ductility of the members and the joints so that the structure is capable to undergoing large inelastic deformations without collapse when subjected to overloads (Mendis & Goldsworthy, 1995). The main drawback of designing for over-strength is that it does not eliminate the risk of the structure collapsing when the design loads are exceeded. However, designing for improved ductility may be able to prevent the total collapse of the structure even in an extreme event. According to AS 1170.4:1993, it is possible to improve the ductility of structures by adopting the details recommended for intermediate
moment resisting frames (IMRFs). The details adopted are quite similar to those recommended as earthquake resistant details by Dowrick (1977), Pinto (1987) etc.

When subjected to earthquakes, the points of contraflexure in columns change and columns can even be subjected to single curvature, thus leading to increases in bending moments (Park & Paulay, 1975). Such changes occur due to the influences of higher modes of vibration, particularly second and third modes. Thus, in columns, plastic hinges can occur at the beam column junctions, and may cause destruction of columns due to crushing of concrete when the confinement is insufficient. According to Woodside (1995) that most of the buildings failures in Japan's Kobe 1995 earthquake have occurred due to poor detailing of columns in buildings. In this earthquake, nearly 82,000 buildings had collapsed and a similar number suffered partial collapse. In order to avoid such failures, links in columns and location of splice bars will need special care.

The reinforcement details recommended for columns in Dowrick (1977) is given in Detail Sheet No 1. It can be seen that the column reinforcement splices are located away from beam column junctions since plastic hinges occur at these locations. The amount of links are also increased close to the beam column junctions. These details differ from the Standard Method of Detailing adopted in Sri Lanka where the link spacing is generally maintained at about 12 times the smallest vertical reinforcement bar diameter. The column splices are also located just above the beam column junctions. Thus, it can be seen that the usual detailing practice adopted in Sri Lanka is quite inadequate for columns. Therefore, the chances of columns failing are quite high, which can lead to total collapse of buildings. As reported by Saatcioglu & Bruneau (1993), Mitchell & Tinawi (1992), in Erzincan 1992 and Costa Rican 1991 earthquakes also many buildings with poor column details were completely destroyed. In many other buildings, damage was disproportionate to the magnitude of the earthquake that had occurred.

In an earthquake, there is an acceleration in the vertical direction in addition to those in lateral directions. These vertical accelerations can induce moment reversals in beams. The change of point of contraflexure in columns can also contribute to this. Thus, beams will need some reverse moment capacity, which means the sections subjected to primarily sagging will need a certain amount of hogging moment capacity and vice versa.

According to recommendations given in AS 3600 (1994), the area of bottom reinforcement provided at support face should be able to resist one third of the design hogging moment when acting in reverse direction. This will help the beam to resist moment reversals resulting due to earthquake loads. It will also ensure proper anchorage of bottom reinforcement specially at external columns. It is necessary to ensure that at any section, the beam can resist either a sagging or a hogging moment of one fifth the magnitude of the maximum hogging moment provided at either support. These details are indicated in Detail Sheet No: 2. These recommendations are a deviation from the normal practice adopted in Sri Lanka, and it may result in some increase in top longitudinal reinforcement at span sections.

In an earthquake, the beam column junctions also will be subjected to extra shear forces and tensile stresses that may not exist with static behaviour, which can lead to cracking as shown in Figure 3. Therefore, beam column junctions also will need extra links to prevent failure of concrete (Mendis and Goldsworthy, 1995). These additional links can prevent
cracks that can lead to deterioration of bond between reinforcement and concrete, thus causing significant strength and stiffness degradation. Once a joint fails, the capacity to transfer seismic and gravity loads can be lost, possibly resulting in partial or complete collapse of the structure. The extra links required are shown in Detail Sheet No: 1. This is an important deviation from the detailing recommended in Standard Method of Detailing as practiced in Sri Lanka. In the general details adopted, no links are provided within the depth of the beam at beam column junctions.

It can be seen that the adoption of earthquake resistant detailing in moment resisting frames is not a difficult task. The extra reinforcement required will mainly be necessary to prevent crushing failure of concrete by providing additional shear links. The extra main reinforcement requirement will be limited only to lightly loaded beams where small diameter hanger bars would need replacement with larger bars.

**Blast Resistant Reinforcement Details**

When reinforced concrete elements are dynamically loaded due to blasts, the elements deflect until such time as the strain energy of the element is developed sufficiently to balance the energy delivered by the blast load. If this energy cannot be developed without fracture, then fragmentation of concrete will occur. Therefore, special details are required, which will ensure load carrying capacity of the member, even when fragmentation of concrete does occur. This can be achieved by providing compression reinforcement that is equal to the tension reinforcement provided. In the presence of adequate links, such beams will be able to carry significantly high loads (Institution of Structural Engineers, 1995). This detail is required only for the ground and first floor beams where the blast effects can be quite severe. This means that the blast resistant construction of beams will need a further increase in reinforcement to resist moment reversals than those specified for earthquake resistance at these levels.

It is recommended that the joint details shown in Figure 4 should be used at beam column junctions (The Institution of Structural Engineers, 1995). However, with this detail, the beam reinforcement is anchored in the column where plastic hinges can occur in earthquakes. This recommendation is therefore not desirable with respect to earthquake details. The reason for such recommendation is to ensure that the beam will not separate from the column, when no links are provided within the depth of the beam. However, in earthquake detailing as shown in Detail Sheet No 1, there are links provided for the column reinforcement within the depth of the beam. These links will be able to prevent the separation of the beam and the column even when the beam reinforcement is anchored within the depth of the beam. Therefore, it would be advisable to comply with earthquake resistant details recommended for beam column junctions with respect to both earthquakes and blasts.

The blast pressure that enter the structure through the shattered windows and the failed curtain walls will load the underside and subsequently the top surfaces of the floor slabs along the height of the building. There will be a brief time for which floors will receive a net upward loading (Ettouney et al., 1996, Mainstone, 1976). This upward load requires that the slab be reinforced to resist loads opposing the effects of gravity. It is recommended that top reinforcement should be provided over the complete area of first floor slabs and ground floors which have been designed as suspended (The Institution of
Structural Engineers, 1995). This is a deviation from the earthquake detailing where continuation of top and bottom reinforcement is required only in cantilever slabs. This is a deviation from the normal details adopted in Sri Lanka for slabs as well.

When concrete columns are subjected to blast loads, there is a possibility for total elimination of a column. In such instances, the upper floor columns and beams can act as a lattice girder when the number of upper floors are large and those are capable of forming a lattice girder. However, in low rise buildings such as those with less than five floors, it is possible that adequate ties are not provided and hence may not be able to form such lattice girders. It should be noted that ties are specified for building having five or more storeys in BS 8110 (1985). It is suggested by Elliot et al. (1992) that even a building with less than five floors should be designed such that removal of one element will cause only local collapse. Therefore, the provision of ties should be adopted for two storey and above for reinforced concrete buildings that will be constructed in Sri Lanka in future.

These indicates that adoption of the earthquake resistant detailing in reinforced concrete structures will be able to improve the structure to comply with most of the blast resistant requirements. The extra details are required only in beams and slabs located above the ground and first floor levels.

COST INCREASES DUE TO EARTHQUAKE AND BLAST RESISTANT DETAILING

One of the main reasons for not adopting earthquake and blast resistant detailing for normal construction is the fear that it would increase the cost of construction appreciably. In order to evaluate the probable cost increases associated with adopting earthquake and blast resistant details, a comprehensive cost analysis was performed for a range of different structural forms.

Cost Study No: 1: In this study, a representative sample of structures covering various spans and the associated beam and column sizes that can be encountered in buildings were designed and detailed with normal details and earthquake resistant details. Then, the cost of the structures were evaluated to determine the possible cost increases due to adopting the earthquake details. The earthquake resistant detailing used were those given in Dowrick (1977). The detailing given in AS 3600(1994) are also very much similar to those given in Dowrick (1977). In order to cover a wide spectrum of spans and associated structural forms, a number of different grid sizes were considered.

The details of the cases considered and the results of the cost analysis are given in Tables 1, 2 and 3. The cost figures used for the analysis are as follows, which includes labour, material and markup to cover profits and overheads.

a. Cost of 1m$^3$ of concrete = Rs 5700/=  
b. Cost of 1m$^2$ of shuttering = Rs 500/=  
c. Cost of 1 Tonne of reinforcement = Rs 55,000/=
Table 1: Details of building and dead and imposed loads used for analysis

<table>
<thead>
<tr>
<th>Case</th>
<th>Column size (mm x mm)</th>
<th>Beam size (mm x mm)</th>
<th>Slab details</th>
<th>Grid spacing (m x m)</th>
<th>Dead load (kN/m²)</th>
<th>Imposed load (kN/m²)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>225 x 225</td>
<td>300 x 225</td>
<td>125 solid</td>
<td>3.6 x 3.6</td>
<td>6.5</td>
<td>3.5</td>
</tr>
<tr>
<td>2</td>
<td>300 x 300</td>
<td>350 x 225</td>
<td>125 solid</td>
<td>4.5 x 4.5</td>
<td>6.5</td>
<td>3.5</td>
</tr>
<tr>
<td>3</td>
<td>450 x 450</td>
<td>500 x 300</td>
<td>150 solid</td>
<td>5.0 x 5.0</td>
<td>7.1</td>
<td>3.5</td>
</tr>
<tr>
<td>4</td>
<td>600 x 600</td>
<td>600 x 300</td>
<td>175 solid</td>
<td>6.0 x 6.0</td>
<td>7.3</td>
<td>3.5</td>
</tr>
<tr>
<td>5</td>
<td>750 x 750</td>
<td>650 x 350</td>
<td>425 rib slab</td>
<td>7.5 x 7.5</td>
<td>8.3</td>
<td>3.5</td>
</tr>
<tr>
<td>6</td>
<td>1000 x 1000</td>
<td>750 x 400</td>
<td>425 rib slab</td>
<td>8.0 x 8.0</td>
<td>8.3</td>
<td>3.5</td>
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Table 2: Increase in cost with earthquake resistant detailing where columns contain 1% reinforcement.

<table>
<thead>
<tr>
<th>Case</th>
<th>Column size (mm x mm)</th>
<th>Column spacing (m)</th>
<th>Beam size (mm x mm)</th>
<th>Total cost per 100 m² of area</th>
<th>% Cost increase due to EQR detail</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Normal detail</td>
<td>EQR detail</td>
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<td>225 x 225</td>
<td>3.6</td>
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<td>300 x 300</td>
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<td>3</td>
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<td>4</td>
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<td>1000 x 1000</td>
<td>8.0</td>
<td>750 x 400</td>
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Table 3: Increase in cost with earthquake resistant detailing where columns contain 2% reinforcement.

<table>
<thead>
<tr>
<th>Case</th>
<th>Column size (mm x mm)</th>
<th>Column spacing (m)</th>
<th>Beam size (mm x mm)</th>
<th>Total cost per 100 m² of area</th>
<th>% Cost increase due to EQR detail</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Normal detail</td>
<td>EQR detail</td>
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<td>518504</td>
<td>529878</td>
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</tbody>
</table>

The cost analysis was performed using the columns provided with 1% and 2% reinforcement. For each case, the cost of constructing an area covering 100 m² was considered with normal detailing recommended in British practice and those recommended for earthquake resistant design. Further details of the cost analysis can be found in Perera and Jayasinghe (1998).

It can be seen from Tables 2 & 3 that the resulting increase due to adopting earthquake resistant detailing is only about 3.5% of the structural cost for spans above 5.0 m and less than 1% for spans less than 4.5 m. Since the structural cost of large buildings varies between 40 - 50% of the total cost, the resulting increase in the total cost will be less than 2% for large spans and less than 0.5% for small spans.

Cost Study No: 2: In this cost study, a four storey reinforced concrete framed building with roof deck was considered. The slab, beam and column sizes were determined by considering an imposed load of 3.5 kN/m². The building size was 24 m x 24 m with a 6.0
m grid. The foundation was a raft with a thickness of 600 mm. The slab thickness was 165 mm. The edge beams were 450 mm x 225 mm and the internal beams were 450 mm x 300 mm. The columns were 300 mm x 300 mm. The costs were determined for the normal design as adopted with reinforcement details recommended in BS 8110, for earthquake resistant detailing, for earthquake resistant detailing with blast resistant detailing for the ground floor and first floor beams. The cost figures are given in Table 4. The cost increases were calculated as with respect to the normal design.

<table>
<thead>
<tr>
<th>Building element</th>
<th>Normal design (BS 8110 detailing)</th>
<th>Earthquake design</th>
<th>Earthquake and Blast resistant design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foundation (raft)</td>
<td>2,453,061.00</td>
<td>2,453,061.00</td>
<td>2,453,061.00</td>
</tr>
<tr>
<td>Columns</td>
<td>548,123.00</td>
<td>597,561.00</td>
<td>597,561.00</td>
</tr>
<tr>
<td>Beams</td>
<td>2,615,758.00</td>
<td>2,653,073.00</td>
<td>2,758,805.00</td>
</tr>
<tr>
<td>Slabs</td>
<td>4,193,214.00</td>
<td>4,193,214.00</td>
<td>4,476,794.00</td>
</tr>
<tr>
<td>Total cost (Rs)</td>
<td>9,810,156.00</td>
<td>9,896,909.00</td>
<td>10,286,221.00</td>
</tr>
<tr>
<td>% cost increase</td>
<td></td>
<td>0.88%</td>
<td>4.85%</td>
</tr>
</tbody>
</table>

This indicates that blast resistant design can increase the cost of the structure by about 4.85%. Thus the overall cost increase can be about 2.5% of the total cost of the building. However, for taller buildings, the cost increases due to enhance blast resistance is likely to be smaller since the increase in reinforcement is associated only with the elements above ground and the first floors.

CONCLUSIONS AND RECOMMENDATIONS

Earthquake resistant details are not often adopted in countries that are considered as free of earthquakes since they are located away from the well known plate boundaries. Blast resistant details are also not generally adopted since the threat of blasts is not often considered seriously enough by the architects and structural design engineers. It is shown that the approaches needed with respect to structural forms against blast and earthquake resistance are somewhat similar and hence could be easily adopted at the conceptual and preliminary design stages. Once a suitable structural form is selected, the earthquake resistance can be further enhanced by improving the ductility of the structure. It is shown that the enhanced blast resistance will only need some additional reinforcements for the beams and slabs above the ground and first floors.

It is shown that the total cost increase for small span structures is in the range of 0.5% which indicates that the adoption of earthquake resistant detailing is quite worthwhile. In the case of buildings with large spans, the resulting increase is only about 2%. When blast resistant details are also included, the cost increase can be in the range of 2.5%.

In Sri Lanka, two to three storey buildings are extensively used as school buildings, government offices, banks etc. Heavy damage to these buildings can result in many casualties and also difficulties in recovery of casualties/survivors after an earthquake or blast. Therefore, it may be advisable to make it mandatory to adopt good structural forms, and earthquake and blast resistant details for such buildings.
The present trend in Sri Lanka is for main private sector companies to use large elegant buildings with many floors as their main offices, large multistorey buildings as shopping malls and super markets etc. Such buildings can have a large number of people at one location and building failures in events of earthquakes or blasts would result in a large number of fatalities. Thus, it may be advisable to make it mandatory to adopt good structural forms, and earthquake and blast resistant details for such buildings as well.

REFERENCES


The Institution of Structural Engineers (1989), Standard Method of Detailing Structural Concrete, London.

The Institution of Structural Engineers (1995), The structural engineers' response to explosion damage, London, 23 p.


Figure 1: Geometric irregularities that are acceptable in plan for regular buildings

Figure 2: Setbacks allowed in regular buildings

Figure 3: Forces in interior in exterior joints(from Mendis & Goldsworthy, 1995)

Figure 4: Joint details recommended (from Institution of Structural Engineers, 1995)
Detail Sheet No 1: Earthquake resistant detailing of columns (Dowrick, 1977)
TYPICAL BEAM REINFORCEMENT
FOR EARTHQUAKE (IMRF)

External

Detail Sheet No 2: Earthquake resistant detailing in beams
(Sanders, 1995)

Internal

NOTES:
1. ALL TIES (LIGATURES) TO BE CLOSED
2. MINIMUM OF 2 BARS TOP & BOTTOM.
   REFER TO BEAM SCHEDULE FOR ALL
   BAR AND TIE SIZES.
3. TIE SPACING $S_t$ TO BE THE
   LESSER OF:
   - 0.25 EFFECTIVE DEPTH OF COLUMN = 0.8D
   OR 8 TIMES MINIMUM COLUMN BAR DIAMETER
   OR 24 TIMES LIGATURE DIAMETER
   OR 300mm