COST COMPARISON BETWEEN NORTH AMERICAN CODES AND BRITISH COLLAPSE MEASURES

B. D. CHARNISH
Yolles Partnership Inc., Toronto, Canada

Abstract

The British Standards and Building Regulations include progressive collapse and key element design measures for the structural design of high-rise structures. The Canadian and American Codes at present do not generally incorporate these measures to the same extent. The structure of both a reinforced concrete beam and slab system and a structural steel beam system for buildings of varying height will be compared using Canadian, American, and British Standards.

This paper will provide a review of the specific code clauses and an estimate of the structural cost premium, based on a normalized design, with costs provided by Canadian, American, and British Contractors and Sub-contractors. These costs will be further reviewed in comparison with the overall structural costs, the over-all building costs, and the overall development costs.

The intent of the comparison is to provide a guide to Owners and developers in considering the premiums associated with the above code provisions for structural integrity of the building structure.

Keywords: Codes, Standards, Structural Integrity, Progressive Collapse

1. Introduction

The British Standards\(^1\), \(^2\) and Building Regulations\(^3\) include progressive collapse and key element design measures for the structural design of high-rise structures. The Canadian and American Codes at present do not generally incorporate these measures to the same extent. It is the intent of this paper to explore the premium costs on a representative building between the two approaches. This exercise will assist in the potential incorporation of the British collapse prevention strategies into the North American Codes.

This paper will describe the differences in the Codes with respect to the progressive collapse and key element design requirements, the design requirements for structural integrity under an ordinary design condition, the Code requirements for hazard approach to design and the safety measures required to prevent the progressive collapse of the structure.

Using both reinforced concrete and structural steel materials, we will consider the design of a representative building structure to estimate the cost premium. Using these estimates, clients can be informed about the possible premiums to at least include the British Standards and Regulations approach to the structural design of high-rise buildings in North America.

The British Standards and Regulations approach is generally:

(i) Provide horizontal and vertical ties to allow the substantially deformed structure to span as a catenary above a damaged column or wall.

(ii) If effective horizontal tying is provided and it is not feasible to provide effective vertical tying of any of the vertical load bearing members, then each such untied member is considered to be notionally removed one at a time in each storey in turn to check that its removal would allow the rest of the structure to bridge over the missing member, albeit in a substantially deformed condition.

(iii) In considering this option, it should be recognized that certain areas of the structure (cantilevers or simply supported floor panels) would remain vulnerable to collapse. If it is not possible to bridge over the missing member, that member should be designed as a protected member or key element.
(iv) The area at risk of collapse of the structure within the storey and the immediate adjacent storey is limited to 15% of the area of the storey or 70 m², which ever is less. The area at risk is the area of the floor subject to collapse on the removal of the member.

(v) Design of protected members or key elements requires that the accidental loading should be chosen with regard to the importance of the key element and the consequences of failure. The key element should always be capable of withstanding a load of at least 34 kN/m².

2. Discussion of the National Building Code of Canada Structural Integrity Requirements

The National Building Code of Canada (NBCC) requires buildings and their structural members to have sufficient structural capacity and structural integrity to safely and effectively resist all loads and events that may reasonably be expected during the service life of the building. In Commentary “C” of the supplement to NBCC to this Code, the definition of structural integrity is noted as the ability of the structure to absorb local failure without widespread collapse that is a failure of the substantial portion of building totally disproportionate in magnitude to the initial failure, known also as a progressive collapse.

With respect to the structural integrity in the ordinary design condition the NBCC states that building structures designed in accordance with the Canadian Standards Association (the material standards for design) will possess an adequate degree of structural integrity, generally through detailing requirements for connection between the components. The CSA6 A23.3 and CSA S16 Standards for Design of Concrete Structures and Limit States Design of Steel Structures, respectively, confirm this approach in the text. This implies that for building structures designed in accordance with these Standards, no quantitative evaluation of structural integrity should be necessary insofar as the ordinary design conditions are concerned. The Code indicates that situations where structural integrity may require additional special attention include, amongst others, buildings exposed to severe accidental loads such as vehicle impact or explosion.

According to Part 4 of the NBCC, buildings are designed for dead, live, seismic, wind, snow, soil, and hydraulic pressure as a matter of course, but there are loads and events of less frequent occurrence that could cause a failure of the building not addressed by the Code. Accidental events with probability of occurrence higher than 10E-4 have to be identified and measures need to be taken to ensure adequate structural safety exists. These measures include: control of events causing abnormal loads, design of ties using ordinary specified loads, design for alternate load paths in damaged structures, design to resist abnormal loads and control of widespread collapse, control of events includes installation of protective device such as curbs, and guards against vehicle impact.

Design of ties using ordinary specified loads relates to an attempt to provide alternate load paths without consideration of specific damage scenario and specific load paths. This “deemed to satisfy” method is relatively well developed for precast panel buildings and much less for cast-in-place concrete buildings. This approach is even less well developed for steel framed buildings.

Design for alternate load paths in a potentially damaged structure (bridging) is a design process where a structure has been designed to bridge the region damaged by an abnormal event. According to the Canadian Portland Concrete Association Handbook, this basic method of design for structural integrity includes the following:

The designer should consider the effect of removal, one at a time of:

(i) one span of any floor or roof element;
(ii) one column or hanger in any one storey;
(iii) one length of bearing wall panel for any storey equals to 1.5 the storey height, unless those panels are prefabricated when this length is equal to the panel length; and
(iv) the load combinations to be considered are Rf greater than or equal to D + 0.5L + 0.2W or Rf greater than or equal to D-0.3W.
There are a number of ways in which the necessary load resistance might be developed in a damaged structure including: beam action of walls, catenary (membrane) action of floor slabs, change in direction of floor or roof slab span, good floor plan strong points, and adequate diaphragm action.

The design to resist abnormal loads (design of key elements) considers if the removal of element by an accident would initiate progressive collapse, that element must be designed to remain functional when such an accident occurs. It is acknowledged that this is a last resort design and that other approaches should be considered. In the case where this strategy is employed, the designer should rationalize (for the building in question) the magnitude of the loads that may be reasonably anticipated. The following loads were proposed for inclusion in the Code, but not adopted; therefore the load has been left up to the designer to rationalize the intensity. According to the Canadian Portland Concrete Association Concrete Handbook, when this was considered by the Code Committee, the suggested loads that elements supporting vertical loads should be designed to withstand a uniformly distributed horizontal load of 44 kN/m over a one-storey height and a vertical load consisting of the specified dead load plus 50% of the live load and 20% of the wind load. Exterior bearing walls at corner should be designed for horizontal loads of 135 kN distributed over the storey height for the outer 1.5 m length of the wall adjacent to a corner and the vertical load as above. Indispensable structural elements other than columns or corner wall elements should be designed for a lateral force of 33 kN/m2 and a vertical load as above. The lateral force should be assumed to act perpendicular to the element over the adjacent areas that are capable of transmitting the force to the element in question. The structure should be divided into areas separated by planes of weakness that prevent collapse in one area from propagating into adjacent areas.

3. Discussion of the British Standards Structural Integrity Requirements

The British Building Regulations and Standards include a normal method of ensuring robustness by provision of the vertical and horizontal ties. It may be assumed, according to the standards, that if Clauses C1.2.2.2 for reinforced concrete structures and Cl. 2.4.5.3 with Cl. 2.1.1.1 and Cl. 2.4.5.2 that the BS requirements have been met for reducing the sensitivity to disproportionate collapse and further action is not likely necessary.

The British Building Regulations and Standards include a normal method of ensuring robustness of the provision of the vertical and horizontal ties. It may be assumed, according to British Standard 8110-1:1997 Cl. 2.2.2.2 that:

Structures should be planned and designed so that they are not unreasonably susceptible to the effects of accidents. In particular, situations should be avoided where damage to small areas of a structure or failure of single elements may lead to collapse of major parts of the structure. Unreasonable susceptibility to the effects of accidents may generally be prevented if the following precautions are taken:

(i) All buildings are capable of safely resisting the notional horizontal design ultimate load as given in Cl3.1.4.2 (All buildings should be capable of resisting notional design ultimate horizontal load applied at each floor or roof level simultaneously equal to 1.5% of the characteristic dead weight of the structure between the mid-height of the storey below and either mid-height of the storey above or the roof surface. ... ) Applied at each floor or roof level simultaneously.

(ii) All buildings are provided with effective horizontal ties (Cl. 3.12.3) 1) around the periphery; 2) internally; and 3) to columns and walls.

(iii) The layout of building is checked to identify any key elements the failure of which would cause the collapse of more than a limited portion close to the element in question. Where such elements are identified and the layout can not be revised to avoid them, the design should take their importance into account. Recommendations for the design of key elements are given in Cl. 2.5 of BS 8110-2: 1985.

(iv) Buildings are detailed so that any vertical load bearing element other than a key element can be removed without causing the collapse of more than a limited portion close to the element in question. This is generally achieved by the provision of vertical ties in accordance with 3.12.3 in addition to satisfying (i), (ii), and (iii) above. There may, however, be cases where it is inappropriate or impossible to provide effective vertical ties in all or some of the vertical load bearing elements. Where this occurs each such element should be considered to be removed in turn and elements normally supported by the element in question designed to bridge the gap in accordance with the provisions of 2.6 of BS 8110.2:1985.
**Figure 1: Reinforced Concrete Flat Slab**

**Legend**
- **Horizontal Ties**
  - Distributed longitudinal and transversal internal ties = continuous bottom bars in slab, both directions. (For clarity purpose shown in top right slab corner only)
  - Perimeter tie
  - Column ties, capable of developing a force equal to 3% of total design ultimate load carried by a column at particular level.

**Sections**
- **Section 7-A**
  - According to CSA A23.3 for ordinary design condition
- **Section 7-A**
  - With BS 8110 tie design requirements implemented
FIGURE 1: REINFORCED CONCRETE FLAT SLAB

HORIZONTAL TIES - LEGEND

- DISTRIBUTED Longitudinal AND TRANSVERSAL INTERNAL TIES - CONTINUOUS BOTTOM BARS IN SLAB, BOTH DIRECTIONS. (FOR CLARITY PURPOSE SHOWN IN TOP RIGHT SLAB CORNER ONLY)
- PERIPHERAL TIE

COLUMN TIES, CAPABLE OF DEVELOPING A FORCE EQUAL TO 3% OF TOTAL DESIGN ULTIMATE LOAD CARRIED BY A COLUMN AT PARTICULAR LEVEL.

SECTION "A-A"

ACCORDING TO CSA A23.3 FOR ORDINARY DESIGN CONDITION

SECTION "A-A"

WITH BS 8110 TIE DESIGN REQUIREMENTS IMPLEMENTED
FIGURE 2: REINFORCED CONCRETE SLAB ON BEAMS

HORIZONTAL TIES - LEGEND

--- TRANSFERSAL INTERNAL TIES - CONTINUOUS BOTTOM BARS IN BEAMS.
--- CONDITIONAL INTERNAL TIES - CONTINUOUS BOTTOM BARS IN BEAMS AND LINTELS.
--- PERIPHERAL TIE

COLUMN TIES, CAPABLE OF DEVELOPING A FORCE EQUAL TO 5% OF TOTAL DESIGN ULTIMATE LOAD CARRIED
BY A COLUMN AT PARTICULAR LEVEL.

SECTION "A-A"

ACCORDING TO CSA A23.3 FOR
ORDINARY DESIGN CONDITION

SECTION "A-A"

WITH BS 8110 TIE DESIGN
REQUIREMENTS IMPLEMENTED
**Figure 3: Composite Steel-Concrete Deck on Steel Beams**

**Horizontal Ties - Legend**

- Steel members used as internal ties - Connections designed to resist tie forces.
- Reinforced concrete members used as internal ties.

Steel members used as column ties - Connections capable to resist a force equal to 1% of total design ultimate load carried by a column at particular level.

**Section “A-A”**

According to CAN/CSA-S16.1 for ordinary design condition

- PL 10 x 110
- 3x3/4" A325

**Section “B-B”**

With BS S580 tie design requirements implemented

- PL 10 x 110
- 3x3/4" A325

Slab steel not shown
### Table 1. Reinforced Concrete Building: Flat Slab

<table>
<thead>
<tr>
<th>Structural Component Based on Sub Trade Price Without General Expense and Fee</th>
<th>Base Building Cost Per Square Foot of Gross Building Construction</th>
<th>Added Cost (Per Square Foot)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formwork, Concrete Placing, and Floor Finishing</td>
<td>Can$16.20</td>
<td>Nil</td>
</tr>
<tr>
<td>Concrete Supply</td>
<td>Can$6.20</td>
<td>Nil</td>
</tr>
<tr>
<td>Reinforcing Steel</td>
<td>Can$5.60</td>
<td>Can$0.10</td>
</tr>
<tr>
<td>Miscellaneous Related to Penthouse Areas and the Like</td>
<td>Can$1.00</td>
<td>Nil</td>
</tr>
<tr>
<td>Estimated Cost of Structure for the Superstructure</td>
<td>Can$30.00</td>
<td>Can$0.10</td>
</tr>
<tr>
<td>Premium of approximately 2 tonnes per 2150 sq. m typical floor or 0.94 kgms per sq. m. On percent basis, less than 0.40 of one per cent of the cost of the structure.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimated Cost of the Building for the Superstructure</td>
<td>Can$133.00</td>
<td>Negligible premium.</td>
</tr>
</tbody>
</table>

### Table 2. Reinforced Concrete Building: Beam and Slab

<table>
<thead>
<tr>
<th>Structural Component Based on Sub Trade Price Without General Expense and Fee</th>
<th>Base Building Cost Per Square Foot of Gross Building Construction</th>
<th>Added Cost (Per Square Foot)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formwork, Concrete Placing, and Floor Finishing</td>
<td>Can$17.20</td>
<td>Nil</td>
</tr>
<tr>
<td>Concrete Supply</td>
<td>Can$5.70</td>
<td>Nil</td>
</tr>
<tr>
<td>Reinforcing Steel</td>
<td>Can$6.10</td>
<td>Can$0.25</td>
</tr>
<tr>
<td>Miscellaneous Related to Penthouse Areas and the Like</td>
<td>Can$1.00</td>
<td>Nil</td>
</tr>
<tr>
<td>Estimated Cost of Structure for the Superstructure</td>
<td>Can$30.00</td>
<td>Can$0.25</td>
</tr>
<tr>
<td>Premium of approximately 5 tonnes per 2150 sq. m typical floor or 2.37 kgms per sq. m. On percent basis, less than 1 of the cost of the structure.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimated Cost of the Structure for the Superstructure, including Cladding, Mechanical and Electrical and Elevating etc.</td>
<td>Can$135.00</td>
<td>Can$0.25</td>
</tr>
<tr>
<td>On percent basis, less than 0.2 of one per cent of the cost of the superstructure of the building.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3. Hybrid Reinforced Concrete Core with Rolled Steel Floor Framing and Exterior Steel Columns

<table>
<thead>
<tr>
<th>Structural Component Based on Sub Trade Price Excluding General Expense and Fee</th>
<th>Base Building Cost Per Square Foot of Gross Building Construction</th>
<th>Added Cost (Per Square Foot)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reinforced Concrete Core</td>
<td>Can$8.40</td>
<td>Can$0.10</td>
</tr>
<tr>
<td>Structural Steel Floor Framing Including Connections and Insert Plates</td>
<td>Can$14.80</td>
<td>Can$0.10</td>
</tr>
<tr>
<td>Steel Deck and Mesh Reinforced Concrete</td>
<td>Can$6.80</td>
<td>Nil</td>
</tr>
<tr>
<td>Fire Protection</td>
<td>Can$1.00</td>
<td>Nil</td>
</tr>
<tr>
<td>Estimated Cost of the Structure for the Superstructure</td>
<td>Can$31.00</td>
<td>Can$0.20</td>
</tr>
<tr>
<td>Estimated Cost of the Building for the Superstructure</td>
<td>Can$137.00</td>
<td>Can$0.20</td>
</tr>
</tbody>
</table>

Conclusions

The National Building Code of Canada and the Canadian material standards have been developed with an eye to increased integrity provisions. These measures have been given a “face” by identifying an approach to design and an indication of forces to be used in design. The NBCC has limited the applicability of the more robust structure to higher levels of probability (that is greater than 10E4). In many respects the AISC Standards and the ACI Standards have increased their awareness with respect to built-in integrity; and the ACI Standards have increased their awareness with respect to built-in integrity details but have not identified the design approach and forces as the British Standards.

This exercise has demonstrated that a significant increased level of protection can be afforded by the British Standards with a rather trivial cost to project to the extent of being negligible. This paper concludes that designers incorporate these provisions in their design as a matter of life safety even though the events that trigger these requirements are hopefully few and far between.

Acknowledgements

This paper acknowledges the contributions of Walters Steel Limited, Hamilton, Canada in the area of pricing and PCL Constructors Inc., Toronto, Canada for their assistance in pricing the various options and components.

References