Review of NBCC earthquake-resistant design requirements for cladding connectors

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As a consequence of recent increases in the severity of seismic design force requirements in Canada, practicing engineers who design cladding connectors should be concerned with their seismic resistance. The current design requirements of the 1990 edition of the National Building Code of Canada for nonstructural components call for unduly high prescribed design forces for the cladding connectors without providing justification, commentary, or substantiation for this constraint, nor guidance on how this is to be achieved. This paper offers some rationalization of these stringent design requirements based on a review of their evolution, outlines some of the shortcomings of the current design approach, recommends possible abatements of the requirements in special cases, and points toward future directions and alternate philosophies for the design of cladding connectors. In particular, the following are recommended: (*i*) the scope of Part 4 of the National Building Code of Canada should be modified to specifically indicate that cladding connectors are to be designed by a professional engineer, (*ii*) the latest cladding-connector seismic-resistant design philosophy of the Structural Engineers Association of California should be incorporated into the National Building Code of Canada; (*iii*) a distinction should be made between out-of-plane and in-plane cladding-connector seismic-resistant design requirements; (*iv*) a commentary should be written on cladding-related seismic-resistant design issues to clearly state current philosophy, uncertainties, and limits of knowledge be included in the building code, and (*v*) standardized seismic-resistant cladding connectors be developed with capacities to meet prescribed levels of ductile behavior and interstory drifts and widely distributed to the profession.

Key words: cladding, connectors, earthquake, design, code, seismic.

Comme conséquence de l'accroissement de la rigueur des exigences de calcul relatives à la force sismique, les ingénieurs qui conçoivent les assemblages de revêtement extérieur devraient s'inquiéter de leur résistance aux séismes. Les exigences de calcul de l'édition 1990 du CNBC pour les éléments non structuraux imposent des forces de calcul élevées sans offrir de justification, de commentaire ou d'explication pour cette contrainte, ni de marche à suivre pour la respecter. Cet article examine ces exigences de calcul en fonction de leur évolution; il souligne certaines lacunes de la méthode de calcul actuelle, recommande certains relâchements des exigences dans des cas spéciaux et propose des avenues possibles au niveau de la conception des assemblages de revêtement extérieur. En particulier, les auteurs recommandent ce qui suit : (*i*) que le but de la partie 4 du Code national du bâtiment du Canada soit modifié de manière à s'assurer que les assemblages de revêtement extérieur soient conçus par des ingénieurs professionnels; (*ii*) que la philosophie de calcul parasismique de la SEAOC pour les assemblages de revêtement extérieur soit intégrée au Code national du bâtiment; (*iii*) qu'une distinction soit faite entre les exigences de calcul parasismique pour la résistance des assemblages en plan et hors plan; (*iv*) qu'un commentaire soit rédigé sur les questions relatives aux assemblages de revêtement extérieur afin de faire le point sur la philosophie actuelle et les incertitudes et de faire en sorte que les limites de la connaissance soient indiquées dans le code du bâtiment; (*v*) que des assemblages de revêtement extérieur parasismiques types soient développés en respectant les niveaux prescrits de ductilité et de flèche horizontale relative des étages.

Mots clés : revêtement extérieur, assemblages, tremblement de terre, conception, code, sismique.

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1. Introduction

The responsibility for the architectural and structural designs of cladding panels and cladding connectors in North America, to put it mildly, is ill defined. Although many manufacturers, fabricators, architects, and structural engineers deliberately attempt to avoid the issue, for expediency or simply to escape liability, the growing number of cladding distress and failures eloquently illustrates why this situation cannot last longer (Cohen 1991).

There has been a recent burst of research activities throughout Canada in a relatively new field legitimately called building sciences, a hybrid of architecture and structural engineering. A large part of this broad field is concerned with the overall performance of the building envelope. Inevitably, since many building scientists are currently structural engineers by training, they naturally approach the cladding and cladding connector design problem as one of simple statics, with compliance to the National Building Code of Canada (NBCC) (Associate Committee on the National Building Code 1990) as a necessary requirement.

In nearly all Canadian cities the seismic design requirements now exceed those related to wind. Consequently, the few practicing engineers who design cladding connectors must deal with the seismic-resistant design requirements of the 1990 edition of the NBCC for nonstructural components. These currently call for unduly high prescribed design forces for the cladding connectors without providing justification, commentary, or substantiation for this constraint, nor guidance on how this is to be achieved. This causes a particular prob-

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lem. Given the state of practice in this industry, such an unexplained design criterion which appears irrational and constraining is unlikely to be used, let alone used adequately, if detrimental in a highly competitive bidding process. Without condoning violations of mandatory design requirements, it is equally poor engineering practice to blindly apply a design directive whose logic cannot be retraced or understood. Hence, the aforementioned concerns must be acknowledged, and further clarifications provided.

This paper volunteers some rationalization of these stringent design requirements based on a review of their evolution, outlines some of the shortcomings of the current design approach, recommends possible abatements of the requirements in special cases, and points toward future directions and alternate philosophies for the design of cladding connectors. The earthquake-resistant design of the cladding panel itself is beyond the scope of this paper, and has been discussed by others (Arnold 1989; Sack et al. 1989; Cohen and Powell 1991).

2. Evolution of North American Codes

2.1. Early code development in the U.S.

Since the introduction of the curtain wall in the late 1920s and precast concrete cladding panels a few decades later, cladding has usually been regarded as nonstructural. However, paradoxically, it is subsequent to their catastrophic structural failures that earthquake-resistant cladding design requirements were included in building codes.

For example, during the 27 March 1964 Anchorage, Alaska, earthquake, a major portion of the reinforced concrete J.C. Penney building suffered significant damage due to a torsional failure. According to Berg and Stratta (1964), "the center of rigidity was far removed from the center of mass, and the earthquake-induced rotational displacements caused the west wall to shear at the second floor level at the north end and drop several feet. Most of the four-inch precast panels in the north wall were shaken loose and fell to the ground ..." Granted, this building may have had an inherent design flaw, but the panels should not have detached themselves from the building, thus jeopardizing life-safety.

Throughout the U.S.A. prior to the 1980s, the prevailing philosophy advocated large cladding-connector earthquake-resistant design forces as a conservative but inexpensive measure. According to Rosenbluth (1980), "With the connection or anchorage providing the sole means of attachment of some elements to the structure, such that the connection provides both the vertical load and the seismic force resistance, design should be at least conservative enough to provide for construction tolerances, unexpected loadings, greater-than-design earthquakes and the variability of workmanship. For this reason, it has been accepted practice in the United States to require a far greater design force for the attachments of exterior panels to the structure than for the panel itself." The design concept entailed essentially fixing the cladding panel at each floor using high-strength rigid connectors cast into concrete. Although these connectors would obviously fail suddenly and in a brittle manner, engineers confidently believed these were designed to resist elastically the "real level forces" (Mr. E.G. Zacher, Principal and Structural Engineer, H.J. Brunnier Associates, San Francisco, private communication, 21 August 1992).

This was the design philosophy of the second and third editions of the Recommended Lateral Force Requirements of the Structural Engineers Association of California (SEAOC) (Seismology Committee of the Structural Engineers Association of California 1966, 1973), which required that nonstructural elements and parts of structures be designed to resist a force, F_p, equal to the product of Z, C_p, and W_p. For cladding and connectors, C_p was a seismic coefficient, W_p was the weight of the cladding panel element, and Z was a numerical coefficient that depended on the seismic zone in which the structure was located. Generally, a C_p of 0.3 was required for panel design, but the connections had to be designed for a C_p of 2.0. Hence, the design force for the connectors was required to be 6.67 times that of the cladding itself. Shortly thereafter, when the SEAOC seismic requirements were adopted into the Uniform Building Code (e.g., International Conference of Building Officials 1976), an importance factor, I_p, was introduced and the equation became

$$[1] \quad F_p = ZI_pC_pW_p$$

where I_p was specified in addition to the C_p factor. Values for the importance factor ranged from 1.0 to 1.5, but the importance factor had more to do with continuity of function than risk to life.

Thus, according to the 1976 Uniform Building Code, cladding connectors for cladding panels of an ordinary building (I_p = 1.0) located in San Francisco, where Z = 1.0, would have been designed to be able to resist a force of F_p = $2.0W_p$. This can be interpreted as ensurance that cladding connectors will remain elastic until maximum absolute floor accelerations reach $2.0g$. An assessment of the level of safety afforded by this provision is possible by considering the following:

(*i*) The expected maximum peak ground accelerations in San Francisco are typically of the order of $0.5g$ (Housner 1990).

(*ii*) The Newmark–Hall acceleration amplification factor to obtain a mean-plus-one-standard-deviation (84.1%) linear elastic response spectra for 5% damping is 2.7, for a corresponding maximum pseudo-acceleration value of $1.35g$ in the low period range.

(*iii*) The SEAOC design recommendations were to be used in a working stress context, using allowable connector capacities which are generally very conservative.

(*iv*) For parts of connectors, ultimate strength was at least 20% larger that working strength (recall than working stress seismic codes in the U.S.A. commonly permitted a 33% increase in allowable stresses in the presence of earthquake loads).

On this basis, and assuming that possible additional force amplifications due to the cladding own's dynamic response are negligible, designing the connectors for 6.67 times the design force for the cladding panel appears sufficiently conservative.

However, while the above code requirements seem logical for earthquake excitations in the out-of-plane direction of the cladding panel, they are not for the in-plane direction. In-plane, interstory drifts control the behavior of the panel connections, because the attachment points must either follow the floors to which they are connected or prevent interstory drift altogether. For most modern cladding, the latter is possible only to a limited extent. Hence, a logical cladding connector design philosophy should, instead, aim at permitting large and unrestrained interstory displacements, or alternatively, ensure that the cladding connectors can accommodate these displacements in a ductile manner. This thinking permeated subsequent editions of the SEAOC recommendations.

2.2. SEAOC 1980

Rethinking of the philosophy for the design of cladding connectors started shortly after the 9 February 1971 San Fernando earthquake. Zacher (personal communication, 1992) indicated that a few tests were conducted after the earthquake on the existing connector types. Observations included nonductile cone failures in the concrete and bar buckling in cases of improper fastening. This led to requirements in the 1980 edition of the SEAOC recommendations (Seismological Committee of the Structural Engineers Association of California 1980), to ensure that the (steel bolt) connectors are designed to have some flexibility, by lowering the required design force levels and, thereby, introducing an element with some ductility.

The commentary to the 1980 edition of the SEAOC recommendations describes this shift in philosophy as follows: "The tendency toward higher force levels is felt to be inappropriate for exterior elements because higher strength connections are not necessarily ductile or capable of accepting the required floor to floor displacements. The former arbitrary high value of $C_p = 2.0$ for connection has been deleted in favor of an emphasis on the performance of the connection. The current provisions result in a $C_p = 0.3$ for the wall panel, an equivalent $C_p = 0.4$ (i.e., 1.33 times 0.3) for the body of the connector, and an equivalent $C_p = 1.2$ (i.e., 4 times 0.3) for the connector fasteners. It is assumed that the additional design capacity of the fasteners (e.g., inserts, welds, dowels, or bolts) will force any potential excess distortion to occur in the more ductile connector body (e.g., structural steel angles, rods, or plate) rather than the more brittle fastening." Thus, the 1980 edition of the SEAOC recommendations required that exterior nonstructural elements be designed for $F_p = ZIC_pW_p$, but explicitly stating that the importance factor, I, be 1.0 for the entire connection. This edition of the SEAOC recommendations also requires (*i*) that these nonstructural elements be capable of accommodating the true ultimate story displacements resulting from lateral forces; (*ii*) that bodies of connections be designed with sufficient ductility and rotation capacity so as to preclude fracture of the concrete or brittle fractures near the welds; (*iii*) that elements of connection embedded in concrete be attached to, or hooked around, reinforcing steel to effectively transfer forces to the reinforcing steel; and (*iv*) that the above requirements are also applicable to panels in one-story structures, i.e., panels having their base connected to foundation (this is a significant departure from the previous design approach).

It is noteworthy that these requirements remained essentially identical in the subsequent editions of the SEAOC recommendations, and that the National Earthquake Hazards Reduction Program (NEHRP) (Building Seismic Safety Council 1988) guidelines, which associates expected level of seismic performance with various level of life-safety, also follows this philosophy. However, in all cases, commentaries to the above codes acknowledge that the numbers are judgmental and are not based on research, although experience has not shown them to be unsafe.

Clearly, as an alternative, subsequent development aimed at introducing sliding connectors with maximum unrestrained displacement equal to the code-specified interstory drift calculations. Typical such sliding connectors currently used in U.S. seismic zone 4 are presented elsewhere (McCann 1991). However, special care must be taken when following such an approach, as the adequacy of the drift calculations for serviceability, and, hence, the adequacy of the allowable movement in the sliding connections, are still questioned.

2.3. National Building Code of Canada

Historically, Canadian code-writing committees have found much inspiration in the Californian seismic-resistant design provisions. In particular, cladding and cladding-connector design requirements have closely followed the SEAOC recommendations, but not beyond those contained in the 1973 SEAOC edition. Indeed, adoption of the aforementioned 1980 SEAOC philosophy into the NBCC has been delayed to this day. It is conjectured that the past and current states of cladding-design practice in Canada were partly responsible for such a deferral, but in view of the deficiencies of the current NBCC approach in this regard, a change to the latest SEAOC philosophy is overdue, and more than likely in future editions of the NBCC.

In the meantime, the SEAOC 1973 philosophy is embedded in the NBCC, but with the significant difference that the cladding connector is designed for 10 times the cladding design value, as opposed to the 6.67 ratio reported above for the 1973 SEAOC edition. Unfortunately, the rationale for this striking discrepancy is apparently lost, as no substantiation of this decision could be found during an in-depth review of all archived minutes of the past meetings of the Canadian Committee on Earthquake Engineering (CANCEE), going back to the first meeting in March 1965, and no other documentation to this effect could be found in the open literature.

Based on the above comparison, the writers believe that the NBCC already has a built-in importance factor of 1.5, probably introduced by an a priori judgment that the failure of a cladding panel connector is a life-hazard worthy of this extra protection. This would explain the boost-up of the cladding-connector design force ratio from 6.67 in the SEAOC 1973 edition to 10 in the NBCC. Paradoxically, as the historical development which led to the current NBCC provisions for cladding-connector design is not documented, a change to clause 4.1.9.1.(14) of the NBCC was proposed in early 1989 with the intent to introduce an importance factor, I_p, to the existing cladding-connector design equation; with a maximum value of I_p of 1.5, the new cladding-connector design force ratio would have reached 15. This proposed change was rescinded subsequent to the public review process when serious concerns were raised as to its rationality.

Finally, the current NBCC has no special provisions explicitly aimed at precluding failures in the concrete into which the attachments are cast, or other similar local failures likely if the full connector's design force is to be transmitted to the backup structure or cladding panel.

3. Outline of existing deficiencies

The database of knowledge on the seismic performance and design of cladding connectors is still relatively limited. In fact, even a recently published book on cladding design (Wang 1992) fails to adequately present the current issues, and does not refer to the most recent practice and research findings. While usual publication delays can explain some of these shortcomings, it remains that no state-of-the-art report exists to assist practicing engineers in the design of satisfactory earthquake-resistant cladding connections. This should not be surprising because, in the U.S.A., "building designers normally treat the curtain wall as non-structural, and often leave the choice of cladding and its connections to the architect and cladding manufacturer" (Goodno and Palsson 1986). Unfortunately, chances to learn from past mistakes are limited. For example, during the 17 October 1989 Loma Prieta earthquake, there were several instances of cladding connectors failing to perform as intended, causing cracks in the precast concrete panels (this was reported by private communications to the second writer by San Francisco–Bay Area practitioners, but without building locations, because building owners did not want to release this information to the public).

In summary, it is recognized that (*i*) there exists little understanding of the seismic behavior of the connectors and cladding panels; (*ii*) analytical models of the clad building are few and do not recognize the nonlinear behavior of the cladding components; (*iii*) design guidelines are insufficient; (*iv*) design practices are inconsistent; and (*v*) more research is urgently needed (Earthquake Engineering Research Institute 1984).

Although most building codes, including the NBCC (clause 2.5.2.1.(1)), explicitly allow for the use of alternative design methods, in the above perspective, this would be difficult for the case at hand. At best, for out-of-plane response only, the structural engineer may be able to demonstrate that the importance factor of 1.5 implicit in the NBCC equation is unnecessary, leading to the reduction of the connector's design force by 33% in circumstances where certainty exists that no loss of life is possible by the failure of the cladding connections and separation of the cladding panel from the structure.

As a minimum, an immediate transition to the latest and more rational SEAOC and NEHRP philosophy should be viewed as a priority. Eventually, a more rational cladding and cladding-connector seismic-resistant design philosophy should be developed and adopted. An overview of work in that direction follows.

4. Future directions

The structural roles of cladding are not well defined, and can be seen in the lack of architectural and history of technology literature on the developments in (structural) cladding design. Architectural history indicates that the use of heavy precast concrete cladding may have started as a competitor to lightweight curtain walls, even though precast concrete panels possess significantly larger masses than curtain walls. Although, over the past 70 years, cladding has usually been regarded as nonstructural, recent research has demonstrated its significant effect on the behavior of structures. Cohen and Powell (1991) noted that "studies of response of tall buildings support this statement, because measured deflections tend to be smaller than computed deflections (Miller 1972). In addition, Henry and Roll (1986), Goodno and Palsson (1986), and PCI (1989) have shown that precast concrete cladding has a significant influence on the behavior of clad frames. Differences were found between clad and unclad frames for lateral displacement, natural frequency, and frame member force distribution. Significant forces were present in panel-to-frame connections. Davies and Bryan (1982) concluded that 'stressed skin action is present whether the designer acknowledges it or not.'"

"Since even 'non-structural' cladding has a significant effect on structural behavior, it is natural to ask whether performance under wind and seismic loads can be improved by explicitly utilizing the stiffness and strength of the cladding. The question is particularly pertinent for seismic performance, using energy dissipating cladding-to-frame connections to add lateral strength, lateral stiffness, and damping to buildings. There are possible applications in both new construction and seismic retrofit. In addition, there can be an increased flexibility in the use of interior space, because some or all of the interior lateral bracing can be omitted," as noted by Cohen and Powell (1991).

There is a need for innovative and affordable seismic retrofit schemes for existing, older buildings, due to the weakened economy and lack of new construction. The schemes should provide supplemental lateral strength, lateral stiffness, and energy dissipation and damping without destroying established and potential interior architectural functions. Presently, almost all retrofit schemes offer only improvements in seismic performance. Very few schemes, if any, rehabilitate buildings, offering improvements to the day-to-day operation of buildings.

Currently, building owners are improving their investments architecturally, by replacing the cladding to modernize facades, improve the natural lighting within the building, and better control the heat transmission and loss to and from the building's interior (Harriman 1992). Combining these improvements with an energy-dissipating cladding system will provide building owners with an enticing combination of benefits as follows: (*i*) building space will be rented more quickly and possibly for more money in a building with a modern facade and contemporary image; (*ii*) the building operation costs will decrease with the use of state-of-the-art technology for natural lighting, and passive or active (or "smart") environmental control devices mounted in or on the facade; (*iii*) renters will be satisfied with the improved natural lighting and environmental control; and (*iv*) building performance during earthquakes will be improved, thus markedly decreasing the possibility of loss of life and property.

To incorporate an energy-dissipating cladding system into the design of structural systems, a rational design procedure must be used. Accepting outdated and (or) established construction practices until a failure occurs, and modifying some of the properties of the connectors after failures or on a whim, do not constitute a structurally rational approach. The function, location, and properties of the connectors must be examined, redefined, and redesigned to act as integral components in structural systems.

Since structural cladding panels must be effective as shear panels, they need to extend over at least one full bay, not partial bays. The multi-functional connectors currently used only at corners of precast concrete cladding panels may not be the most effective and efficient solution. It may be possible to embed a (structural steel) framing system in the precast concrete panels allowing for better connector locations and more reliable anchorage of the connectors. Good engineering judgment dictates that the connectors perform simple, well-defined functions. For example, the connectors supporting the gravity load of the panels should not also perform a function that may lead to a connector failure, such as yielding in the horizontal direction to dissipate energy and provide damping. The connectors, however, may act in parallel, each performing simple functions, such that the failure of one type of connector does not lead to the failure of another type. Simple, well-defined connector functions ensure that the structural behavior of the cladding system and the overall structural

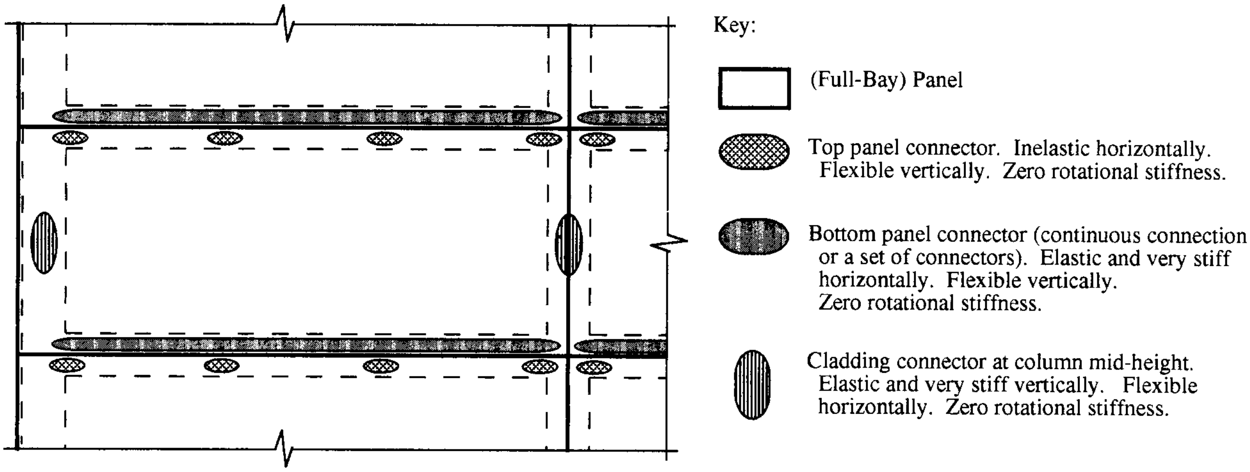

FIG. 1. Design concept for cladding connectors (Cohen and Powell 1991).

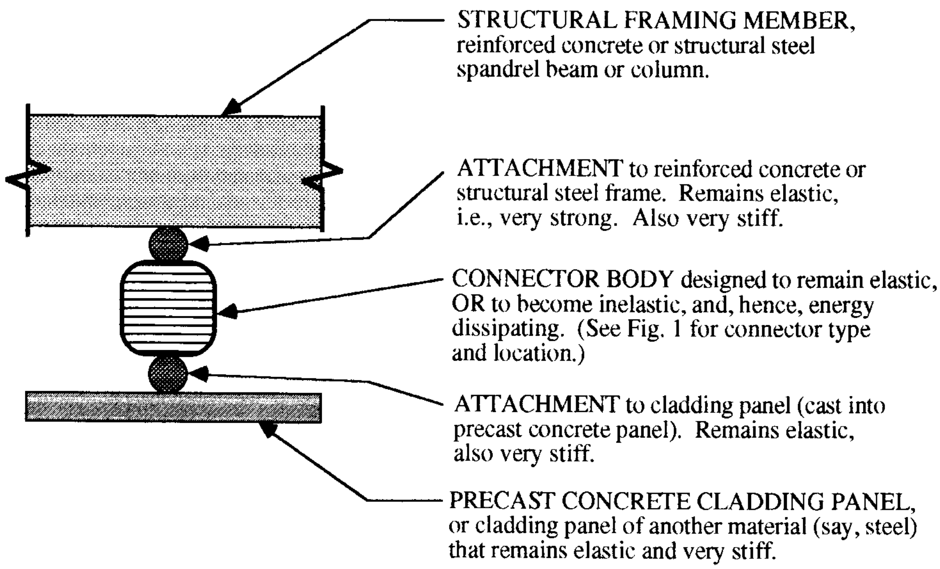

FIG. 2. Terminology for an energy-dissipating cladding system with controlled yielding (Cohen 1993).

system are predictable and that even their nonlinear behavior can easily be represented in analytical models.

One example of a rationally conceived design concept for an energy dissipating cladding system (with steel cladding panels) is given in detail in Cohen and Powell (1991, 1993). In the design concept, the top panel connections are hysteretic yielding, for which the strengths and yield displacements (or, equivalently, the initial stiffnesses) are chosen to participate in the overall structural system. The cladding connectors as part of the energy-dissipating cladding system provide lateral strength, lateral stiffness (and drift control), and damping through hysteretic yielding. For a brief description of the connector locations and functions, the readers are referred to Figs. 1 and 2. For serviceability level ground motions when the building and hysteretic yielding connectors remain essentially elastic, hysteretic yielding connectors may not be sufficient. It may be necessary to use rate-dependent connectors in parallel (either with the cladding system or elsewhere in the building) to reduce amplified horizontal accelerations at the upper stories and protect acceleration-sensitive nonstructural components and roof-mounted equipment (Cohen 1993).

Successful code development for new construction and rehabilitation of structures from research results in this area will entail a coordinated effort among researchers and practitioners in structural engineering, architecture, and construction and fabrication.

5. Conclusions

In light of the review conducted by the writers and described in this paper, the writers recommend the following:

(*i*) Modify the scope of Part 4 of the National Building Code of Canada to specifically indicate that cladding connectors are to be designed by a professional engineer.

(*ii*) Incorporate the latest SEAOC cladding-connector seismic-resistant design philosophy into the National Building Code of Canada.

(*iii*) Distinguish between out-of-plane and in-plane cladding-connector seismic-resistant design and its respective requirements.

(*iv*) Provide a commentary on cladding-related seismic-resistant design issues to clearly state current philosophy, uncertainties, and limits of knowledge.

(*v*) Develop standardized seismic-resistant cladding connectors capable of meeting prescribed levels of ductile behavior and interstory drifts, and distribute widely to the profession.

Some research is already under way to develop safe, reliable, and rational cladding and cladding-connector system for seismic resistance, but a more considerable funding effort from governmental agencies and private industry will be necessary before the objectives stated in Sect. 4 are met.

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