Raising the Bar on Bridge Resiliency, Safety and Security

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ABSTRACT

Comprehensive bridge safety and security must consider a range of potential hazards the bridge may become exposed to during its service life. However, our conventional design approach based on traditional design loads and typical site-specific extreme events (such as wind, scour and seismicity) is somewhat ill-suited for handling the new challenges. The paper introduces the key system properties central to risk mitigation in a complex multi-hazard environment, and summarizes the functional requirements that must be met by such a multi-hazard resilient design, outlining how this could be applied to practical design of bridges from the simple to the complex signature type bridges.

KEYWORDS: Bridge, Resiliency, Safety, Security, Extreme Events, Multi-Hazards, Innovation

1. Introduction

All accepted norms of design based on engineering methods and mechanics, irrespective of the level of sophistication, account for two central issues, ***serviceability*** and ***safety***. The classical allowable stress design ensured both by keeping service stresses below the material strength by a factor of safety. In other words, serviceability was ensured by limiting the service stresses (strains) below material strength by a certain factor of safety while safety was ensured by making the structure strength exceed the service capacity needed by the same factor of safety. This worked well for early structures where the design was governed by relatively deterministic service loads such as dead loads, live loads, anticipated environmental effects such as wind and seasonal variation in temperature. However, ever increasing heights and spans produced structures more sensitive to environmental loads that had to be described in probabilistic terms. The present-day probability-based limit-state design philosophies consider the loads as well as the strength of the structure as probabilistic variables. The load and resistance factors considered for the ***ultimate limit state*** (or strength limit state) ensure the probability that the level of loading exceeding the structure's strength, in other words failure, stays within accepted norms.

In both methods, safety is essentially a matter of structural strength over the expected loads. Consideration of structural strength against loads in some fashion or the other will remain fundamental to engineered structures no matter where the future developments may lead. However, overloading (or adverse load combinations) driven by chance (or probability) producing demand levels that cannot be sustained by the strength of the structure is just one issue out of many issues, or ***hazards***, that could potentially threaten the safety of a given structure. In fact, some of the hazards to structural safety and security involve failure mechanisms that are not effectively mitigated by increasing just the structural strength. The historical development of the state-of-the art in bridge design shows that the recognition of these other hazards has not so much been a steady progression but rather a series of discrete steps driven by catastrophic events acting as the catalysts for further refinement of the design philosophy and process. For example,

- Original Tacoma-Narrows Failure (1940) - Was the catalyst leading to the wide-spread recognition of aerodynamic stability as a key issue for long-span flexible bridges

- Silver Bridge Collapse (1967) - Set in motion the process of development of fatigue and fracture resistant design of tension elements in use today.

- San Fernando Valley Earthquake (1971) - Propelled forward the sense of urgency in mitigating the seismic vulnerability of the national bridge stock and the focus on improving seismic safety and performance.

- Sunshine Skyway Collapse (1980) - Led to the design requirements in use today with respect to providing protection against ship collision.

- The events of 9/11 - Underscored ever present threat to the infrastructure safety from terrorism and the hazards posed by fuel fires whether deliberate or accidental.

- Events following Hurricane Katrina (2005) - Suggest the need to recognize wave action as a potential hazard.

More recent events such as the I-90 Tunnel Ceiling Collapse (2006) and the Minneapolis Bridge Collapse (2007) appear to indicate ***human error*** as a key potential contributor.

Irrespective of the factors leading to the on-set of component failures, subsequent structural collapse would not have occurred if not for the overall ***system fragility***. Issues of a more serviceable nature than immediate threats to safety such as rain-wind vibration of stay cables [1] pedestrian induced vibrations [2] and serious construction accidents due to system instability [3] can be added to the list.

Thus, it can be inferred that the safety and security issues needing consideration in bridge design are many. Slowly but surely the need for consideration of ***multiple-hazards*** in bridge design is crystallizing across the industry.

2. Multi-Hazard Environment

This need for considering multiple-hazards bring some new challenges to bridge design. First, there are conceivable situations where action taken to mitigate one hazard could be detrimental to the mitigation of another. Second, some of the newer hazards such as terrorism, sabotage, accidental loads, blast, fire, last but not least human-error are far less predictable or quantifiable even in probabilistic terms. Third, some of the hazards involve situations or conditions that can be expected to evolve over the life of the structure. Therefore, it is not possible to predict threat levels from certain hazards during the design process that the structure may potentially face during its useful life. Further, many of these hazards involve situations where the demand side of the equation is not readily quantifiable or the resistance side of the equation involves failure mechanisms not related to design strength. Thus our approach in mitigation of these hazards requires pragmatic, indirect solutions that are more effective than facing the hazards head-on by increasing structural strength or resistance. This suggests the need for a fresh look at the present-day approaches to bridge safety and security and refine them as necessary for ***risk mitigation*** within the context of ***multi-hazard exposure***.

The design process once again must be enhanced to keep in step with new realities of this multi-hazard environment so the structures will accordingly be endowed with both resistance and reliability. The hazard selection for a given structure must be addressed in terms of life-safety, the need for a functioning transportation network following a ***hazard event occurrence*** as well as the economic, social and physiological impact of failure resulting from certain hazards over others.

3. Multi-Hazard Effects and Structural Resiliency

The need for system properties other than just strength in mitigating conventional hazards and the application of the bi-level design for hazards with considerable variability was discussed before. However, the number of hazards needing consideration in the present-day multi-hazard environment includes a considerably longer list than those traditionally considered in standard design. These include:

- Wind
- Fatigue
- Corrosion
- Seismic
- Natural disaster driven such as hurricanes, floods, wave action
- Fire
- Blast loading
- Acts of terrorism and sabotage
- Construction and manufacturing defects
- Factors such as lack of knowledge, human error, and negligence

Most hazards listed above are far less predictable than even the worst of extreme environmental loads and thus are not readily amenable to standard design treatment of strength over demand. A design method that adds yet another ***system property*** with wider spectrum of coverage[1] is the best approach in the cost-effective mitigation of this relatively unquantifiable mix of hazards.

The term ***resiliency*** is used herein to describe this ***system property*** of structures designed with multi-hazard resistance as a central theme. In addition to being damage resistant, this system property enables a structure to provide a certain minimum level of functional performance even when key structural elements are completely damaged. As postulated herein, resiliency approach is more successful than strength approach to ***multi-hazard risk mitigation*** where the nature and magnitude of hazards are not precisely predictable. Unlike the previously discussed system properties such as redundancy, ductility etc., ***structural resiliency*** is best described as a set of functional requirements enabled through effective implementation within the whole structural solution than just one aspect of it or an addition later on.

Resilient Bridges can be described as those that are considerably more immune to damage, and when damaged, are resistant to collapse than those meeting traditional design requirements. Bridges that conform to the resiliency concept discussed presently would perform considerably better under various hazard conditions irrespective of the nature of the hazard, whether they are accidental, natural, man-made or oversight. Resilient bridges are first of all less likely to suffer damage under a given hazard event and, second, even if significant damage results from a hazard event of exceptional intensity, they have inherent ability to maintain global stability and are able to continue to function and carry the service loads at safety level of performance. This is

[1] The system properties such as ductility discussed previously are mostly single-issue parameters

achieved through the following three-pronged approach:

- Improved immunity to damage at the member level due to improved structural member composition, innovative application of new materials, and design and detailing concepts where inherent resistance to multiple hazard conditions is systematically enhanced, and hazard mitigation built in.
- Ability to maintain global stability and improved immunity against progressive collapse following significant damage to various key elements and components resulting from improvements and enhancements to the global structural configuration.
- Sufficient residual load carrying capacity and alternate load paths that becomes active under serious localized damage and limited deformations of the roadway following damage

3.1 Functional Requirements for Resiliency

To be considered resilient, the overall structural system, element design and member farming must satisfy the following minimum conditions:

3.1.1. Bridge Element Design Must Incorporate Hazard Resistance

The element design and detailing must incorporate such aspects as Fatigue resistance, Corrosion resistance, Ductility, Fire resistance, Resistance against accidental loads due to collisions and Ability to withstand pre-defined levels of surface pressure due to blast, fluid flow etc. Current standard practice considers some of these resistances whereas others are not considered at all. The recognition of this broader multi-hazard resistance as an essential design consideration would result in bridge structures that are considerably more hazard resistant at the member level than ones in service at present. This would lower the chances of actual damage if subjected to a particular hazard of given intensity.

3.1.2. Ensure System Stability Under Damage

Recognizing that preventing damage under all hazards conditions irrespective of their level of intensity is not possible or economically viable, overall structural configuration must provide a stable system under component or member or local damage where sudden removal of any structural elements, members, or connections may occur. This requires a structural system developed around the following objectives:

- Ensure global stability when key elements, components or local areas are significantly damaged
- Resistant to various progressive collapse mechanisms
- Limited deformations of the roadway following damage to key elements, components or local areas

3.1.3. Ensure Occupant Safety Under Damage

As the bridge may be occupied at the time of damage, it must be capable of supporting not only the self-weight but also the live load and any other service loads normally expected. Further, the deflections or excursions of the roadway following damage should be within limits that can be considered tolerable for bridge occupants. This requires:

- Establishment of service loads likely on the bridge at the time of damage,
- Verification of residual strength capacity to carry the service loads established
- Prediction of transient dynamic deflection response of the loaded structure following various sudden damage scenarios

Compliance with above three functional requirements amount to a process of bi-level design for multiple hazards. The first requirement defines the ***multi-hazard resistances*** or ***functional level performance*** under exposure to low to moderate intensity events. The latter two requirements provide for ***multi-hazard risk mitigation*** or ***safety level performance*** under exposure to high intensity events.

While the structural redundancy is an essential part of a resilient design, not all redundant structures meet the resiliency requirements noted above. In other words, structures that qualify as redundant (or non-fracture critical) do not necessarily meet the requirements for resiliency. The current redundancy criterion is aimed at preventing failures associated with only one hazard, namely metal fatigue due to live (repeated) load effects. Further, current criteria are more qualitative and lack the objective quantifications central to the proposed formal resilient design approach.

4. Implementation of the Resilient Bridge Design

The implementation of the design process begins by defining the following parameters; some of which may require formulation on a structure specific basis; considering not only the importance of the particular bridge to the transportation network but also the tangible and intangible consequences of its failure:

1. Multi-Hazards Identification - important to the safety and security issues within the context of a given bridge or a system.

2. Establishment of Target Hazard Resistances – member performance standards such as minimum desired fire rating, surface pressures and impact loads to be sustained at element level without failure.

3. Development of Member Composition & Detailing – cross section designs that can meet the target hazard resistances established.

4. Special Hazard Mitigation Systems – that would further improve member hazard resistances where needed. Examples include dehumidification systems, sprinkler systems, special coatings and local applications of structural shields and other hardening measures.

5. Consideration of Damage Scenarios – there are multiple structural damage scenarios that must be considered in design. They must be formulated to represent realistic conditions that can be expected but also keeping in mind that prevention of collapse under all scenarios is impractical.

6. Applicable Service Loads – to be considered as present on the bridge at the time of damage, at a minimum should include the self-weight and expected live loads. The requirements outlined in NCHRP 406 for bridge superstructures redundancy can be shown to be approximately equivalent to requiring a residual resistance of at least 1.15 DL + 1.08*(LL+I) where DL and LL+I represent the Dead load and Live Loads used in original design [4]. This makes intuitive sense as providing sufficient margins of safety against fatigue damage where the structural cracks may not be immediately visible and may not be detected and corrected for some time. However, the damage scenarios considered for resiliency are of an easily noticeable magnitude and would result in immediate corrective action. Thus, the use of following reduced load factors in resiliency analysis is deemed justifiable: α DL + β*(LL+I) where $1.0 < \alpha < 1.1$ and $0.5 < \beta < 1.0$. The parameter β should be selected on a structure specific basis to represent typical heavy traffic in striped lanes.

7. Roadway Deflection Limits – the roadway deflections and its time derivatives should be sufficiently low to avoid panic amongst the bridge users present on the roadway at the time of structural damage. Roadway deflections (including dynamic component) within 1 to 2% of the span length can be generally considered acceptable. In addition, structural deflections should not cause mutual impact of members, and preferably be of a magnitude to enable potential repair of the bridge where possible.

Items 1 to 3 involve functional level design considerations or ***hazard resistances*** whereas items 5 to 7 are safety level provisions or ***hazard risk mitigation***. Identification of hazards, improvement of hazard resistances and implementation of mitigation systems are implemented at the member level. The hazard intensities to be resisted and systems to be implemented must consider available technology as well as cost effectiveness. Considerable improvement is immediately achievable by combining conventional materials that complement one another. Use of concrete filled hollow steel sections is one such example (Section 5, case study 2 & 3). This can not only improve overall design efficiency and constructability, but also the blast and fire resistance considerably. Use of cross-sectional configurations that limit damage propagation through the cross section is another simple innovation that can yield immediate benefits. This would be especially useful for application in large structural elements such as tower and pier elements. There is considerable potential for exploring uses of newer advanced materials in supplementing those more conventional within the industry. Also, there are ample opportunities for using supplemental systems for improved hazard resistance. The de-humidification systems for suspension bridges cables is one such example, currently gaining popularity in preventing wire ruptures due to corrosion. However, with multi-hazard thinking, such cable dehumidification systems can be combined with others such as sprinkler systems, Intumescnt coatings and may also incorporate hardening for vulnerable areas. Such applications of multi-hazard mitigation designed and coordinated as one system would result in better cost and implementation efficiencies.

However, as noted previously, the design of members and systems to withstand all hazards at all intensity levels is neither practical nor cost effective. This leads us to the second issue central to resilient bridge design; that the bridge should continue to function following significant local damage. This requires the incorporation of following three aspects in to the design; Ability for maintaining stability when damaged, Residual load resistance and Limited roadway deformations, as further discussed below.

4.1 Development of a Resilient Global Structural Layout

The structural layout must provide a stable system under various damage scenarios and must continue to function at safety level. This requires the development of structural systems that can maintain stability after suffering significant local damage, and is a fundamental requirement in the design of resilient bridges. Its implementation has to be done at the conceptual stage and could prove to be a practical impossibility or cost prohibitive to be implemented as a latter addition.

Implementation of resilient designs must consider ***resiliency as another functional requirement***. Creative application of ***form following function*** design approach can be shown to result not only in resilient but also economical, constructible, and elegant structural forms without a significant cost impact as demonstrated later through the case studies.

4.2 Quantification of Effects

This involves simulation of various damage scenarios on an analytical model pre-loaded with service loads. The simulation must be capable of capturing the transient dynamic response following sudden structural damage as well as predicting any subsequent progressive failures of other members. Thus, the analysis must be capable of capturing geometric non-linearity, material non-linearity and material failure.

Developing structural systems capable of maintaining overall system stability under various damage scenarios, at a conceptual level, is considerably more challenging than ensuring sufficient residual strength in individual members. However, quantification and verification central to resilient design process, though repetitive and somewhat mechanical, requires software packages with high-end analysis capabilities as indicated before. This process involves individual analysis executions for each of the hundreds of member/component damage scenarios and condensing the numerous transient time histories of deflections and member forces to develop various demand envelopes for comparison with member capacities. This analysis and quantification are quite time consuming and tedious within the contexts of general-purpose analysis packages in existence. However, development of a special analysis module would facilitate automation of the repetitive analysis and execution of the computations in a time efficient manner. This is quite within the reach of present-day technology, both software and hardware.

5. Technical Feasibility, Cost Impacts and Benefits of Resilient Bridges

While the conceptual advantages of resilient bridges in multi-hazard risk mitigation is rather self-evident, its suitability for wide-spread applications depends on three issues; first and foremost, technical feasibility, and second, cost impacts, and third, if any cost impacts can be justified based on its benefits.

5.1 Technical Feasibility

There are many examples of bridges surviving significant damage to various key elements without collapse as shown below in Figure 1. These bridges exhibiting resilient performance have received relatively little attention and study, likely due to successful performance being less newsworthy than bridge failures with devastating consequences. While it is highly unlikely that these bridges were originally designed with damage tolerance in mind, their structural layout, geometric proportions, depth to span ratios and other yet unknown factors have enabled them to maintain global stability and residual capacity following damage events.

Figure 1. From top left clockwise – all girders damaged in multi-girder concrete bridge, superstructure cut-through in concrete box girder bridge, pier damage and support loss in multi-girder steel bridge, and through girder fractures in a three-girder bridge where all three girders were damaged.

A wealth of information lay to be discovered in such cases that would help establish ***Best Practices.*** These show that for many of the ordinary girder bridges, simple rules of proportioning and detailing practices, implemented at insignificant extra cost, could make a major difference in providing the added values of a resilient design.

5.2 Case Studies

Based on the author's personal experiences with variety of bridge types – from the simplest to signature complex bridges – it is not only technically feasible, but also has a considerable untapped potential for its realization with minimal cost impacts at the worst. Recognition of this potential could transform the state-of-the art practice in bridge design within a relatively limited time. The technical implementation needs to be established differently for simpler girder bridge types (which account for the vast majority of bridges) than for the more complex signature bridge types, as the latter involves significant – though not insurmountable – challenges that can be met with creative designs and next generation bridge forms as demonstrated through the following case studies. In many cases, resiliency was a useful by-product of careful design development and a process of system optimization.

5.1.1. Case Study No. 1: Curved 68.6m Simple Span Box Girder Bridge

Is a curved, 68.6m (225-ft) long simple span twin box girder bridge (Figure 2). It can be shown through analysis that the overall structural layout of this bridge can meet the safety level functional performance under complete damage to any one of the two box girders anywhere in the span. The full depth transverse diaphragms between the boxes, provided intermittently over the span, facilitate load redistribution from the failed girder to the other within a relatively limited portion of the span. This ensures its ability to maintain global stability as well as its ability for carrying service loads with minimal deflections of the roadway slab even for this curved relatively long simple-span bridge.

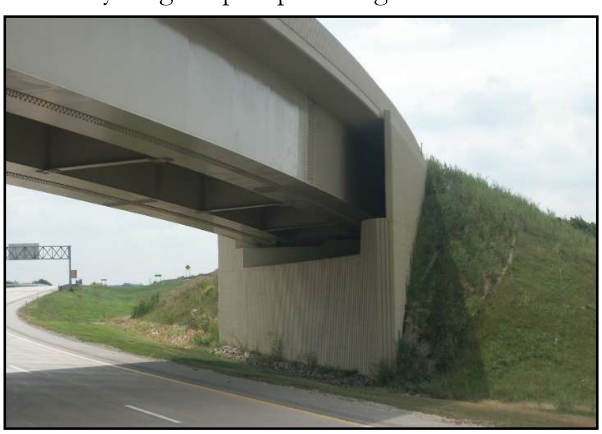

Figure 2. Case Study 1

5.1.2. Case Study No. 2: 137m Span 8-Lane Tied Arch Bridge

The concept tied arch design shown in Figure 4 (right) was developed as a potential alternative to tied-arch bridge applications involving wide roadways often necessitating multiple arch bridges (an example shown left). The concept solution consists of two ribs arranged in a cross formation thus bracing one another at mid span. Multiple hanger planes support transverse floor-beams continuous across the entire roadway. In addition to conventional tie girders, the design also includes under-deck secondary ties arranged in cross formation. It can be shown that the concept design can be developed to achieve resilient performance under damage to arch-rib, tie-girder and multiple hangers, all of which are quite challenging circumstances for traditional designs.

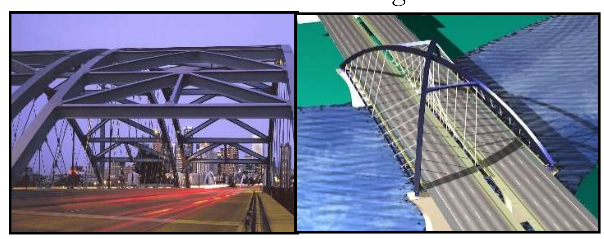

Figure 3. Case Study 2

5.1.3. Case Study No. 3: 265m Span Two-Track Railway Arch Bridge

This 256m span, two-track railway arch bridge (Figure 3) was designed for a site with considerable constructability challenges. Safety, security, design efficiency and constructability have been central in the development of this design-build project. Its functional requirements include providing all structural members with ability for withstanding a certain external pressure loading, providing the bridge with ability to carry one train with removal of any of the key structural elements and components. The damage scenarios include complete damage to one arch rib or removal of spandrel columns and diagonals. In addition, a sensor system is provided for warning approaching trains of high winds and structural damage. The structural solution developed consisted of a trussed-arch global structure system consisting of three arch ribs.

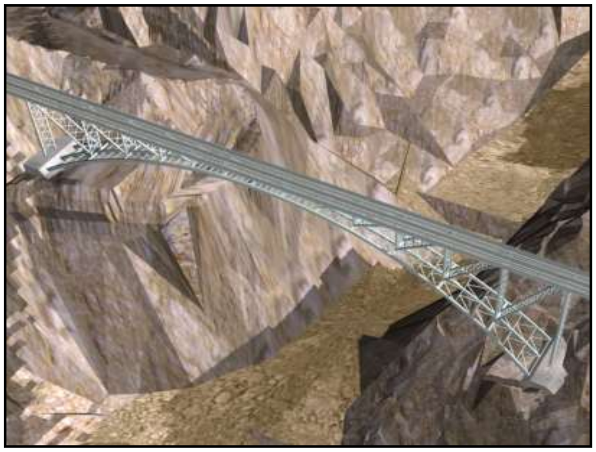

Figure 4. Case Study 3

The arch ribs are provided with in-plane bracing and spandrel columns and diagonals are also trussed. Major structural elements are designed as concrete filled hollow steel sections, not only improving their blast-worthiness, but also fabrication, erection as well as future maintainability. This is another example of a resilient design also offering efficiency, constructability and maintainability advantages over a traditional design.

5.1.4. Case Study No. 4: 274m Main Span, 549m Long Signature Cable-Stayed Bridge

Figure 5 depicts a preliminary design for a 274m main span (900-ft) signature cable-stayed structure. The layout shown is just one variation of several developed along the theme of four cable planes supporting a bridge superstructure consisting of four longitudinal girders and transverse floor-beams framed continuously across the longitudinal girders.

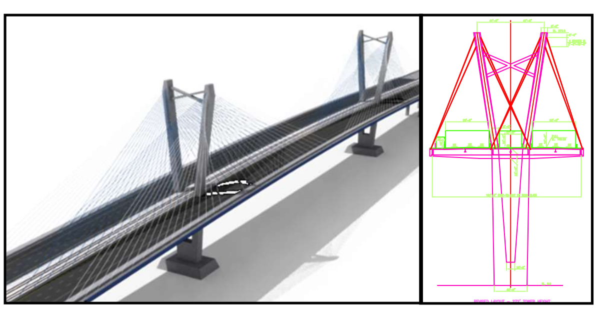

Figure 5. Case Study 4

Preliminary analysis showed that this layout can be developed to provide resiliency with respect to all elements including multiple-cable loss, superstructure damage near the towers as well tower damage at deck level where it is most vulnerable. Below the superstructure, the twin lower tower legs provide complete redundancy. Further, each leg cross section can be detailed with internal barriers to prevent shock wave transmission and damage propagation across the entire section, minimizing the likelihood that any one of the two will be completely damaged under blast loading. This improves the resiliency of these critical lower tower legs even further. Design concepts following this structural layout are the lowest cost options from amongst several other cable-stayed and arch bridge concepts. The material use per unit area of the bridge deck for the proposed design is in fact lower than that for traditionally designed cable-stayed bridges. Thus, resiliency can be viewed as an added benefit of an overall structural system optimized with respect to design efficiency, cost, constructability and serviceability.

6. Attainability and the Pressing Reasons

The technical feasibility, economic viability and the benefits of the proposed design approach was illustrated through case studies as well as real-life examples. It is evident that the broader implementation of resilient designs would make significant advances in improving safety, security and reliability of transportation structures.

6.1 Attainability

Such large-scale transformation of design philosophy as proposed here may appear too ambitious or unattainable at first. The best illustration of the attainability of a large-scale advancement of bridge safety is found in the advancements made in seismic safety. Big push by Caltrans following 1971 San Fernando Valley Earthquake to upgrade the bridges in California has resulted in remarkable accomplishments in seismic risk mitigation, not only in Californian but all over the US and World-Wide. A quick review of the seismic design practices that existed prior the initiative by Caltrans would clearly show the breath and the depth of the accomplishments made within just a few decades.

- 1940: X%DL Applied @ CG in any direction, the % was up to the discretion of the designer

- 1943: F = CW where C=0.02, 0.04 0r 0.06, selected based on foundation conditions

- 1965: EQ = KCD > 0.02D, K=1.33,1.0,0.67 (based on bridge type), C=0.05(T)-1/3 < 0.1 where T is the first mode period estimated using T=0.32(D/P) L/2, D=DL, P=F/Δ

Thus, it was not until 1965 that such basic parameters as even a rough estimation of the first mode period was considered in bridge seismic design. Many large bridges were designed simply for a lateral load equivalent of 5% to 10% (considered generous) of self-weight. The level of sophistication of the design philosophy, analysis and implementation capabilities of design solutions in seismic hazard mitigation makes the state of affairs that existed not too long ago appear medieval.

Reflectively however the present day standard seismic risk mitigation at the time would have appeared totally impractical and prohibitively complex or expensive.

6.2 Pressing Reasons

The news of major bridge failures is not uncommon. In all these cases, system fragility can be seen as the essential factor amplifying the local component failures to catastrophic structural collapse. While it could be argued that prevention of factors contributing to the local failures could have prevented these particular incidences, strength-based design practices and tighter quality control alone cannot totally prevent such future incidences. The number of variables involved and the number of potential scenarios that could result in local failures are just too many. Basic logic suggests that the design procedures based on strength over demand should be supplemented with overall systems that are both robust and reliable. Structural systems developed along the resilient design concept outlined would assure such robustness and reliability by eliminating fragile interdependencies within the structural system. It is only rational to expect that there will be future breeches, unexpected or accidental events and undetected errors in manufacturing, construction, and design resulting either from lack of knowledge, human error or negligence.

It is also clear that the factors leading to these unfortunate failure occurrences are not founded in technical infeasibility or prohibitive costs associated with resilient systems, but the lack of awareness and recognition. These are not very good reasons for continuing the status-quo and forms the best argument in support of the proposed initiative and the pressing need for our timely action.

References

[1] Recent Developments in the Mitigation of Stay Cable Vibrations, IBC Proceedings, 2003 by Kumarasena & McCabe

[2] Vibration of the London Millennium Foot Bridge Parts 1 & 2, Dept CE, U of Cambridge, UK, 2006 by D. Newland

[3]A Rational Design Basis for Top Lateral Bracing of Steel Tub-Girder Bridges, World Steel Bridge Symposium, 2005 by Kumarasena etal

[4] Quantitative Assessment of Structural Redundancy by Computer Modeling, Proceedings TRB, 2005 by Kumarasena