Resilient Bridges- Solution for Bridge Collapse

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Abstract:

Recent research resulted in integration of resilience and risk assessment within the bridge management system. Frequent collapses reported all across the world in the face of dynamism of natural hazard occurrences made it essential to integrate resilience and risk assessment.The possibility of failures occurring was predominantly in ageing and deteriorated bridges. Failures in bridges will increase. Remedial measures design also need to include resilience and sustainability in the designs. Bridge management the world over, veers around the distress symptoms. Enhancement in resilience was never a criterion for allocation of funding. Mono-Criterion approaches focused on distress symptoms will need to evolve into a Multi-Criteria decision-making process.

Introduction

Globally, bridge demography indicates forty-five percent of bridges constructed during Seventies or Eighties, have designed service life of fifty years. All such bridges are nearing the end of their service life. Maintenance had enabled to eradicate all visible symptoms of distress. Fatigue and overloading still persists, rendering such bridges to have distress not visible to the bridge inspection engineer. Bridges without any symptoms are rarely subject to performance monitoring.

Climate changes induced dynamism in frequency and severity of natural hazards is a challenging situation. The occurrences of natural hazards during the past decade has undergone drastic alterations. A frequency of hundred year's event observed to have reduced to five or ten years. Severity of occurrences has also seen an increment over the last twenty years. The reduction in years over which severe events occur and increased severity results in a scenario wherein bridges designed about 50 years ago cannot function safely.

Collapses in bridges, world over have been in news. It was possible to avoid collapses attributable to natural hazards. Bridge engineers relied on region's geographical risk and vulnerability index. There was absence of a connection between the bridge structural status and risk index for the region. Growing dynamism in natural hazards required an urgent need for integration of risk

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assessment of the bridge structure to occurrences of natural hazards. Research focused on the various factors affecting bridge survival. Risk index is related to vulnerability index. Implications of this relationship made it essential to derive bridge structures vulnerability index based on the structural status and geographical vulnerability of the location of the bridge. Historical narrative of a natural hazard decides the geographical vulnerability index. Dynamism of hazards leads to dynamism in geographical vulnerability index. The continuous increasing deterioration in the bridge structure rendered further dynamism in bridge vulnerability index.

Symptom Centric Bridge Management:

The evolution of Bridge Management has focus on Symptoms of distress. It focuses on specific symptoms, like cracks, deflections, corrosion, or unusual load-bearing behavior, which suggests structural or functional distress in a bridge. It required monitoring of these symptoms, to enable engineers assess the bridge's health, identify potential problems before they escalate, to design and implement remedial interventions.

Identification and monitoring of symptoms done using:

- Visual Inspection: Traditional visual inspections are foundational in identifying symptoms. Regular inspections detect surface-level issues like cracks, spalling, or misalignment.
- Sensor Technology: Advanced sensors provide continuous, real-time data on various symptoms, monitoring strain, displacement, temperature, and vibration, to offer valuable insights into the bridge's condition. This came into vogue with the digitization of Bridge management.
- Data Analytics: Utilizing data analytics enhances the ability to detect subtle or emerging symptoms. Trend is to include machine learning and AI. By analyzing historical and real-time data, predictive models can forecast potential failures or maintenance needs.

Symptom Diagnosis

- Root Cause Analysis: Diagnosing symptoms requires understanding the bridge's structural behavior. Diagnosis enables understanding of how factors like environmental conditions, load patterns, and material degradation contribute to observed symptoms.
- Correlation with Design and Load History: Analyzing symptoms in the context of the bridge's design, construction, and load history provides insights related to potential emergence of distress.

Targeted Interventions

- Proactive Maintenance: Focusing on specific symptoms allows for a shift from reactive to proactive maintenance. For example, addressing early signs of corrosion can prevent extensive damage and results in reduction of long-term repair costs.
- Tailored Repair Strategies: Symptom-centric management enables tailored repair strategies that directly address identified symptoms, ensuring effective repairs and efficient resource use.

Case Studies in Symptom-Centric Management

- Crack Monitoring and Mitigation: A bridge with recurrent cracking when fitted with strain gauges and displacement sensors may reveal that thermal expansion and specific load patterns caused the cracks. Adjusting the bridge's expansion joints and provision of reinforcement can mitigate the issue without extensive repairs.
- Vibration Analysis for Fatigue Management: Monitoring long-span bridge using vibration sensors may indicate unusual vibration patterns under heavy traffic. The analysis helps to indentify early signs of fatigue in specific areas. Reinforcing these areas and adjusting traffic management practices may help to mitigate and manage fatigue.

Challenges and Opportunities

While symptom-centric digitized bridge management offers significant advantages, it also presents challenges:

- Data Overload: The vast data generated by inspection records, sensors can be overwhelming, necessitating effective data management and analysis tools to extract actionable insights.

- Cost Considerations: Implementing advanced monitoring technologies and tailored interventions can be costly.
- Skill and Expertise Requirements: Engineers need specialized skills to interpret data and implement symptom-centric strategies. It requires training and skill development.

Symptom-centric bridge management represents a significant evolution in maintaining and ensuring the safety of bridge infrastructure. This approach of focusing on specific symptoms of structural distress, enables more proactive, efficient, and effective management practices. The benefits such as extending the lifespan of bridges, reducing maintenance costs, and enhancing public safety are substantial.

Need Based Evolution:

Over the last three decades, bridge management systems have undergone drastic shift from symptoms to identification of cause of distress in bridges during the mid-life years. Few countries have deployed structural monitoring systems on aging bridges to study the alterations in the performance. This migration from symptoms to cause and performance monitoring emerged from the need to be able to define accurately the deterioration model. Precision in evaluating deterioration significantly enhances the effectiveness of designing remedial interventions. Field acceptance of these advanced features is sluggish and slow. Research thirty years ago in Europe published EN1504, which defined causes of distress. World over performance monitoring has been sporadically implemented.

In recent past, climate changes induced dynamism in frequency and increased severity of natural hazards, challenges bridge maintenance fraternity. Every few years we observe occurrence of a once in hundred year's event with ever-increasing severity. All across the world, natural hazards are causing huge impact on logistic infrastructure. Bridges being at the forefront result in financial loss when bridges collapses. Financial implications have multiple facades. Disruptions in connectivity being the prime reason for a long-term economic instability. The social insecurities arising from such frequent collapses causes investors to differ investment in the regions exposed to such collapses. Loss of connectivity leads to job loss, reduction in efficiency due to longer travel time, increased costs for transportation that together contribute to poor socio-economic stability and reduced economic growth potential in the region.

Coupled with the treat of natural hazards, the demography of bridges implies high percent of bridge population is aging. During implementation of Indian Bridge Management System [IBMS], one of the key finding was that over fifty percent of bridges on National Highways were above thirty years old. In aging bridges, deterioration is present but at times not visible. Aging bridge normally displays reduction in performance and increased fatigue. The design philosophy, during early fifties and sixties, did not provide for safety against increased severity of natural hazards. Together these factors points to a perfect scenario, which aids to increased collapsing bridges.

Collapses are recurring regularly. Frequent loss of connectivity due to collapsed bridge, resulting in economic slow down, huge financial exposure results in the stakeholders demand for a solution. Stopping recurring bridge collapses became a need of the stakeholders to provide a solution. Resilience and risk assessment leading to enhancement of resilience provided a glimmer of hope.

Various international bodies operating in the domain of sustained infrastructure have professed pro-active steps to ensure resilient bridge infrastructure by prevention of risk, manage and reduce risks. This resulted in research getting focus on this integration of resilience and risk assessment within Bridge management system. Geographical vulnerability index and resulting assessment of risk index was in place. The challenge was to evolve a relationship between geographical index and structural status of the bridge structure. It is also essential to understand systemic risk. Influence of risk to bridges is not restricted to loss of connectivity on the logistic network but now encompasses the well being of the whole region and society.

Integrating Risk Assessment of Bridges:

Within India, natural hazards [earthquakes, floods, cyclones, and landslides] pose significant threats to over sixty percent of land area. These hazards are a threat to human life, property, economic stability, and social security. On the logistic network, bridges bear the maximum brunt from these hazards. Their frequency and severity have escalated in recent years, driven by climate change and urbanization. Addressing these challenges requires a proactive approach, focusing on identifying vulnerable areas and implementing mitigation measures, particularly for bridges, which serve as critical infrastructure links. Given their inherent vulnerability, bridges in general and specifically aging bridges require special attention. This necessitates the integration of risk assessment within Bridge Management Systems [BMS]. Research requirements emphasized the systematic and multidisciplinary approach essential for the sustainability of bridges amidst the risk associated with natural hazards.

Methodology deployed involves thorough examination of deterioration mechanisms. This mechanism was further analysed for interaction with natural hazards. This includes analysing impact on deterioration of various environmental factors, such as temperature fluctuations, moisture levels, and chemical exposure. The evaluation includes the impact on bridge materials and structural integrity.

Bridge collapse is not a standalone event; the consequence of a collapse felt on the regional development and stability. The risk assessment process hence entails evaluating the consequences of potential bridge failures, considering impacts on transportation networks, economic losses, and potential harm to human life and the social stability. Data related to the impact of the bridge on the socio-economic aspects to the region essentially need to be studied.

Historical data of the natural hazard is studied. Analysis needs collecting historical data, coupled with an understanding of the geography surrounding each bridge. For India, four primary natural hazards warrant focus: earthquakes, floods, cyclones, and landslides. The northern fringes, particularly near the Himalayan ranges, are more prone to earthquakes and floods, while cyclones predominantly affect the coastal regions. Landslides are a concern in the foothills of various mountain ranges. Research is focused on these four hazards only.

Analysis for evaluation must be on two critical values from historical data: the frequency and severity of hazard occurrences and the uncertainty coefficient, reflecting the increased frequency of events in recent years. Data analysis helps in defining potential damage scenarios, if no action taken to mitigate risks. An important consideration is the propagation of distress within the bridge structure, as frequent events may lead to cumulative damage that could culminate in collapse during future occurrences. Evaluating these progressions is essential for planning effective mitigation strategies.

Consequences encompass potential damage to bridges, disruptions in transportation networks, and possible injuries or fatalities. Consequences vary depending on three critical aspects of each bridge: its design, materials, and traffic intensity. Value of financial cost involved defines consequence. Financial implications include rehabilitation or restoration expenses, along with costs arising from loss of service. Data related to socio-economic impact, if available, allows for a comprehensive evaluation of the costs associated with disruptions resulting from natural hazards occurrence.

Establishing a risk index for natural hazards involves employing mathematical models to quantify the likelihood and severity of hazards occurring at specific locations. Likelihood reflects the probability of a risk event occurring, influenced by factors such as bridge condition, environmental conditions, and usage patterns. For example, bridges in seismically active areas face higher probabilities of earthquakes.

Historical narratives define the rating number assigned to likelihood and consequence of each hazard. These numbers are deployed to evaluate the vulnerability of area for a type of hazards. Vulnerability index leads us to evaluation of risk index. The ratings may categorize likelihood as low, medium, or high, and consequences as minor, moderate, or severe. One additional parameter used is the utility of the bridge and its impact. The final index [vulnerability and risk] calculated using predetermined formulas, based on complex statistical models. This index provides a quantitative measure of overall risk levels associated with each hazard type for that particular bridge. Continuous use in specific regions leads to a more accurate assessment.

The steps for calculating risk indices include:

- Gathering Historical Data: Detailed information about bridge design, construction, maintenance history, and environmental conditions is collected.
- Identifying Hazards: Potential hazards affecting the bridge, such as earthquakes, floods, landslides, and cyclones, categorized.
- Assessing Vulnerability: Evaluate the bridge's vulnerability by considering:

    - Likelihood of service disruption.
    - Likelihood of extreme events based on specific hazard scenarios.
    - Consequences of service disruption.
    - Weight factors assigned based on the importance of each hazard category.

- Calculating Risk Indices: The risk index evaluated from vulnerability index.

The risk index quantifies the probability and severity of natural hazards at specific locations, considering hazard occurrence probability, intensity, proximity, and the vulnerability of the population and infrastructure. It further couples the geographical characteristics with the bridge's structural status. It aids in identifying vulnerable areas, prioritizing mitigation efforts, and evaluating emergency response effectiveness.

Evaluation utilizes risk indices to address natural hazards in bridge management, combining likelihood, intensity, proximity, and consequences to enable effective decision-making. This system calculates a comprehensive risk index for each risk event. This framework include comprehensive risk assessments, resource prioritization, efficient risk mitigation strategies, improved decision-making, and enhanced emergency response planning. By adopting these measures, bridge authorities can better manage risks, ensuring that vital infrastructure remains resilient against natural hazards.

Bridge Collapse: A Reality

Aging process in bridge results in reduction of strength. Historical evidence confirms the fact that beyond a certain age, the reduction in strength that occurs in concrete is far greater than the increase in strength that occurs due to hydration of cement in the concrete. Such reduction occurs due to fatigue and repeated overloading. Bridge structural rating numbers within BMS identifies the level and severity of deterioration process. Bridge Structural Rating number [BSRN] above 3.5 indicates a scenario that defines as deteriorated rather than safe. The only limitation of this technique arises when the simple bridge design becomes complex and different design philosophies come into play.

Most common failure mechanisms in bridges influenced by natural hazards the world over arise from substructure and superstructure failures. Natural hazards generate shear forces on substructure or foundations which results in scouring and shearing of elements. Superstructure experiences unseating or toppling effects Therefore, Failure mechanisms in ageing bridges arise from

- Failure of substructure and foundations due to shear force
- Failures in superstructure due to horizontal force resulting in unseating or toppling of the superstructure.

Both the mechanisms have a potential to start a cascading effect, which finally culminates in a collapse. Horizontal force is the most conspicuous of the force that influences the response of the bridge. The deterioration level in the bridge is available within BMS, this makes it feasible to define the incremental severity of deterioration and resultant reduction in concrete strength. Application of these reduction factors within design equations enables one to establish the probability of the bridge to survive or collapse. This analysis further enables to expand on the probability of survival under varying intensity and severity of natural hazards. Flood velocity increases as the intensity of flood increases. Similarly, the earthquake force intensifies with increase in earthquake scale.

High velocity of water [possibly along with debris due to flooding or landslide] causes scouring in the foundation and high horizontal force on the substructure. Considering a typical geometry of the bridge element/ components, substructure failure observed may initiate two conditions: BSRN above 3.5 and velocity of floodwater exceeding 20 kmph. Transition from safe to marginally safe condition begins when velocity increases above 15 kmph. Circular substructure elements show lower threshold limits for survival as compared to rectangular substructure elements. For rectangular elements, transition from safe to marginally safe starts when velocity increases above 16.5 kmph and results in failure for velocity above 24 kmph. Rectangular substructure and superstructure with deeper sections show reduced probability of collapse. Under few conditions, velocity of 25 kmph is seen before the bridge collapses.

It may be Observed from Table 1 that increasing the diameter of pier from 1.2 to 1.8 meters results in “S” remaining All Safe for velocity varying from 14 to 16 kmph, but “S” defining All Collapse scenario for velocity varying from 18 to 19 kmph.

Table 1 Typical variation of Safety factor “S” illustrated from two tables below:

	Circular Pier of diameter varying from 1.2 to 1.8 meters. Height of pier 8 meters, Concrete M40 and shear rebar 18mm at 150 mm C/C, ABSRN>3.5							
Pier Dia	**Velocity of water flow**							
1.2	9	12	14	15	15.5	16	17	18
1.6	9	12	15	15.5	16	16.5	17	18.5
1.8	9	12	16	16	16.5	17	17	19
Sfactor	1.00	1.00	0.83	0.66	0.50	0.33	0.17	0.00
	All Safe	All Safe	2 Safe,1Mar	1Safe, 2Mar	3 Marginal	2Mar, 1Colla	2Colla,1Mar	All Collapse

Table 2 Girder depth and S factor for varying velocity of water flow

	Girder with depth varying from min dimension 1.5 to 2.5 meters. Width same at 0.75 M, Concrete M40 and shear rebar 18mm at 150 mm C/C							
GIRDE DEPTH	**Velocity of water flow**							
15	9.0	12.0	14.0	15.0	16.0	17.0	18.0	19.0
1.75	9.0	12.0	15.0	16.0	17.0	17.5	18.5	20.0
2	9	12	15	16.5	17.5	18.6	19.8	20.5
2.5	10	13	16	17	18	19	19.5	21
Sfactor	1.00	1.00	0.83	0.67	0.50	0.33	0.17	0.00
	All Safe	All Safe	2 Safe,1Mar	1Safe, 2Mar	3 Marginal	2Mar, 1Colla	2Colla,1Mar	All Collapse

It may be Observed from Table 2 that increasing the depth of girder from 1.5 to 2.5 meters results in “S” remaining All Safe for velocity varying from 14 to 16 kmph, butd “S” defining All Collapse scenario for velocity varying from 19 to 21 kmph. It has to be noted that in both Tables 1 and 2, the Average BSRN is above 3.5.

The superstructure overturning or unseating can be avoided by better support conditions and providing cross bracing. Increased gross weight of the bridge also helps in enhanced resilience.

Earthquake exceeding 6.6 on Richter scale will result in identical response from the bridge.

For the bridge to be resilient under extreme force of natural hazard the bridge geometry will need to be Robust and the deterioration level will need to be low. For the same geometry, the bridge with low deterioration and low strength reduction is probably safe for velocity of flow below 23 kmph / earthquake below “7” on Richter scale.

Bridge management has been reactive, focusing on visible distress symptoms. This mono-criterion approach is effective to identify immediate issues, but it falls short of providing a long-term solution in the face of dynamism of today. The increased frequency and severity of natural hazards challenge the basic assumptions of bridge designs. Research underscores inadequacy of mono-criterion approaches that focus solely on distress symptoms without considering the underlying vulnerabilities that could lead to catastrophic failures. It is crucial for moving from a reactive to a proactive stance, where bridge management is not just about addressing current issues but also about anticipating future challenges. It is essential that a shift towards a broader Multi-Criteria Decision-Making (MCDM) process is essential. MCDM process must consider not only the immediate symptoms but also the broader context of a bridge's structural integrity, its environmental exposure, the socio-economic impact of the bridge, and the potential risks posed by natural hazards.

Conclusions:

Globally the dynamism of natural hazards is the reason for various challenges. United Nations declared 1990 to 1999 as the 'Decade of Disaster Reduction' culminating in the establishment of United Nations office for Disaster Risk Reduction [UNDRR] and Sendai Framework for Voluntary Commitments in the sphere of DRR. UNDRR focuses on anticipating the risk, preparing for the eventuality by early warning, scaling up response capabilities and ensuring resilience.

Research is aimed to bring these aspects into transportation infrastructure. To be able to “ANTICIPATE” the response of the bridges to the dynamism of natural hazards, it is critical to integrate resilience and risk assessment within the Bridge Management System [BMS]. This enables a critical advancement in addressing the growing challenges posed by natural hazards specifically to nearly fifty percent of bridge demography that is aging. The frequency of bridge collapses globally, exacerbated by the dynamism of natural hazards, highlights the urgent need for a comprehensive approach that transcends traditional symptom-centric management. Research has demonstrated that the deterioration of bridges, particularly those constructed over 40 years ago, are reaching a critical juncture. As these structures are near the end of their service lives, the importance of proactive measures that integrate resilience and sustainability into remedial designs cannot be overstated.

Research enables "PREPARE" for the eventuality by providing important knowledge relating to the probability of survival of the bridge. Thereby it ensures all bridges that have lesser probability of survival, accorded required priority for rehabilitation intervention. This action can be proactive rather than reactive. Traditional methods have often relied on static geographical vulnerability indices that fail to account for the evolving nature of natural hazards. The concept of a dynamic vulnerability index, which evolved based on both the structural status of the bridge and the changing environmental conditions, is a significant contribution to the understanding relating to the response of the bridges.

Research enables scaling up of "RESPONSE" by providing sufficient capability to understand the various parameters under which the bridge will survive. It enables to define the possibility of failure or survival for any given scenario. It also provides a tool to define the geometrical changes essential in the bridge to ensure survival. The collapse of a bridge is not an isolated event but one that can have far-reaching consequences for regional development, economic stability, and social security. The loss of connectivity, disruptions to transportation networks, and the resulting economic fallout can lead to long-term instability in the affected regions. This reality underscores the importance of integrating resilience into every aspect of bridge management, from design and construction to ongoing maintenance and monitoring.

In conclusion, research ensures "RESILIENCE" which can be implemented in a proactive manner to enhance sustainability. Integrating resilience and risk assessment into bridge management systems is crucial given the increasing frequency and severity of natural hazards for aging infrastructure. Research outlines a clear path forward, highlighting the need for dynamic risk assessment, advanced technologies, and a Multi-Criteria Decision-Making approach. By adopting these strategies, bridge authorities can enhance the resilience of critical infrastructure, ensuring it remains reliable amid future challenges. Bridge Management must anticipate and mitigate risks in an unpredictable environment. Policymakers and stakeholders should embrace these advancements and implement them widely. They should prepare the bridges today for challenges of tomorrow. To conclude Resilient Bridges provides the solution to avoid collapses.

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