Review of damage criteria and their validation for bridges: a uniform classification framework

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Abstract

A crucial step in assessing bridge condition is the identification and quantification of damage parameters and their associated limit states. To accurately represent the physical damage to bridges, it is essential to establish multiple, well-defined damage states with their limits that can be quantified using appropriate engineering demand parameters. These parameters ensure the precision and reliability of the assessment. While various codes and studies provide qualitative (and in some cases quantitative) descriptions of limit values of damage states, there is a notable lack of widely accepted quantitative definitions specific to bridges. This knowledge gap poses a significant challenge in the field of bridge engineering and damage assessment. Defining threshold values for damage states is a complex task, whether for individual bridge components or for the entire bridge system. The process of defining bridge damage states begins with a comprehensive review of existing codes and guidelines. This initial step involves examining various national and international standards, engineering manuals, and research publications to identify the range of damage states currently recognized in the field. Following this review, each identified damage state is carefully associated with a specific level of structural damage. By refining and standardizing damage state definitions, the reliability and comparability of bridge assessments can be significantly improved, leading to more effective risk management strategies, especially in the context of natural hazards and long-term durability.

Keywords: Bridge assessment, Damage state, Limit values, Structural damage, Risk management.

1 Introduction

Bridges are critical components of transportation infrastructure. Maintaining the continuous functionality of bridges requires ensuring their resilience against various hazards. Post-event field investigations have repeatedly revealed the inadequate performance of infrastructure systems, particularly bridges, when subjected to extreme events such as floods or earthquakes. It is therefore necessary to have robust damage assessment criteria to ensure the safety, functionality, and endurance of affected bridges. Various damage assessment frameworks have been developed to evaluate structural integrity based on factors such as material degradation, environmental influences, and man-made or natural hazards [1–8]. These frameworks typically classify damage states (DS) into distinct levels, ranging from minor to severe, assisting in repair planning and risk assessment.

The validation of proposed damage criteria is essential to ensure the accuracy and applicability across different bridge types and conditions. Common validation approaches include field inspections [9], non-destructive testing (NDT) [10], numerical modeling [11], and experimental studies [12]. Additionally, advanced techniques such as digital image correlation [13], and machine learning-based predictive models [14] have been increasingly used to enhance damage detection and classification accuracy.

Despite these advancements, the variability in DS classification thresholds among different sources introduces subjectivity, posing challenges for standardization and decision-making. This paper reviews existing damage criteria, their classification frameworks, and validation methodologies, highlighting key differences and potential improvements for more reliable bridge condition assessment.

2 Damage state thresholds

Assessing condition of bridge structure requires evaluating the severity and extent of damage. To better identify the relative effect of the damage on the structural response and functionality, this study categorizes bridge components into three groups which are: serviceability elements, secondary structural elements, and primary structural elements.

- **Serviceability elements** support the proper functioning and safety of bridge without bearing significant loads. Those are drainage systems, guardrails, barriers, lighting, pedestrian and bicycle facilities, parapets, crash barriers, maintenance access, noise and vibration control systems, and utilities.
- **Secondary structural elements** are those that ensure the overall functionality of bridge, such as approach slopes, embankment fill, expansion joints, pavement, and backwalls. While they do not directly bear primary loads, they contribute to the usability and operational efficiency.
- **Primary structural elements** (i.e., load-bearing components) directly carry or transfer loads. These include suspension or tie-back cables, bridge decks, beams/girders, piers/columns, abutments, shallow/deep foundations, and bearings.

These categories help assess the DS of various bridge components. A thorough investigation of available literature concerning damage classification is undertaken to identify the most relevant match among the classifications. According to multiple sources [1–8], DSs are classified into five levels. However, thresholds for these classifications vary significantly in the literature, introducing subjectivity into DS determination and corresponding repair actions. Table 1 summarizes the definitions and descriptions of DSs from different reviewed sources. It also provides corresponding socio-economic outcomes, such as comments on repairability and closures. It should be noted that the severity of the damage should be assessed based on the overall condition of the structural system, considering the distribution of damage across all bridge elements. Specifically, the feasibility of structurally repairing heavily damaged bridges (graded as DS4 or DS5), which have already been designated for retrofitting by decision-makers or owners, needs to be evaluated to ensure the success of the overall retrofit interventions [15].

Damage state	Notes	FEMA HAZUS 2020 [1] Country: USA	Hose et al [2] Country: USA	Liao and Loh [3] Country: China	Basoz and Mander [4] Country: USA	Liu and Xiang [5] Country: USA	Lehman et al. [6] Country: USA	Mackie and Stojadinovic [7] Country: Canada	Burghardt et al. [8] Country: Germany
DS1	Definition	Null	No	N/A	N/A	Null	N/A	Null	Null
	State of Damage	N/A	Barely visible cracking						
	Residual deformation in members								
	Bridge functionality		Fully operational			0 days closure		Immediate access	
	Performance level		Cracking					Vertical load capacity loss < 5%	
	Remarks	for earthquakes	No repair for earthquakes	for earthquakes				Traffic remaining < 100%	
DS2	Definition	Minor	Minor	Slight	Slight	Slight	Minor	Slight	Minor
	State of Damage	Minor cracking and spalling at the abutment, cracks in the shear keys at abutments, minor spalling and cracking at hinges, minor spalling at the column, or minor cracking in the deck	Onset of hairline cracks	Minor cracks and spalling in the column, abutment, girder, or deck, expansion joint, or approach slab	Cracking and spalling		Hairline cracks		Loss of handrail, guardrail, and decorations, small-scale (<1 m^2) detachment of pavement, clogging of road drainage
	Residual deformation in members		Cracking < 1 mm						
	Bridge functionality		Operational			7 days closure	Full service/ Fully operational	Weight restriction	
	Performance level		Yielding					Vertical load capacity loss < 20%	
	Remarks	Cosmetic repair	Possible repair					Traffic remaining < 75%	
DS3	Definition	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
	State of Damage		Open cracks, onset of spalling		Abutment and backwall collapse		Open cracks, spalling		Minor to moderate cracks in concrete (<50 cm), light exposure of reinforcement
	Residual deformation in members	<5.0 mm (abutment)	Cracking > 1 mm and < 2 mm Spalling 1/10 of cross-section						
	Bridge functionality		Life safety			30 days closure	Delayed operation	One lane open only	
	Performance level		Initiation of local mechanism					Vertical load capacity loss < 35%	
	Remarks	Economic threshold for repair	Minimum repair				Epoxy injection and concrete patching	Traffic remaining < 50%	

DS4	Definition	Extensive	Major	Extensive	Extensive	Extensive	Severe	Major	Major
	State of Damage	Column exhibiting moderate shear cracks, general cracking, and spalling (while remaining structurally sound), moderate movement of the abutment, significant cracking and spalling of shear keys, any connection with cracked shear keys or bent bolts, keeper bar failure without unseating, rocker bearing failure, or moderate settlement of the approach.	Very wide cracks, extended concrete spalling/spalling over full local mechanism region.	A degraded column without collapse or shear failure, substantial movement at the connections, and significant misalignment of the abutment.	Pier concrete failure		Buckling, bar fracture, concrete crushing		Large cracks in concrete (>50 cm), pervasive cracks in concrete (>1 m), settlement, displacement, tilting, and demolition of piers, demolition of the superstructure and individual abutments, scouring of the piers, large scale removal of building fabric (>1 m3)
	Residual deformation in members		Cracking > 2 mm and concrete spalling in the range of ½ cross-section depth						
	Bridge functionality		Near collapse			120 days closure	Stability issue/Closed	Emergency access only	
	Performance level		Full development of local mechanism					Vertical load capacity loss < 50%	
	Remarks	Extensive reconstruction with intrusive repair	Repair				Replacement of damaged section	Traffic remaining < 25%	
DS5	Definition	Extreme	Local Failure/Collapse	Complete	Complete	Complete	N/A	Extreme	Collapse
	State of Damage	Any column collapsing and connections losing all bearing support, potentially leading to imminent deck collapse, or tilting of the substructure due to foundation failure.	Visible permanent deformation, buckling/rupture of reinforcement	Partial collapse or significant movement of connections, deck unseating, and substructure tilting due to ground failure.	Deck unseating, pier collapse				Complete collapse, demolition (afterwards)
	Residual deformation in members		> 2 mm crack in concrete core and measurable dilation > 5%						
	Bridge functionality		Collapse			365 days closure		Closed	
	Performance level	Collapse or almost collapse state	Strength degradation					Vertical load capacity loss > 50%	
	Remarks		Replacement	Replacement				Traffic remaining = 0%	

2.1 Defining the damage states

Using Table 1, the DSs used in this paper are summarized, outlined and defined in Table 2, which incorporates extend of damage, repair possibilities, and socioeconomic factors. The qualitative descriptions for each categorized damage state are as follows:

- **Damage State 1 (DS1)**: This state represents negligible damage in the overall assessment. Serviceability elements may experience minor to moderate damage, and there might be cosmetic issues in other bridge components. However, no significant repairs are needed, and any repairs required are cosmetic in nature.
- **Damage State 2 (DS2)**: DS2 characterizes minor damage to primary structural elements or moderate to major damage to non-load-bearing components like serviceability and secondary structural elements. The overall damage is slight, and the bridge remains functional, with no major impact on serviceability. However, some repair work may be necessary.
- **Damage State 3 (DS3)**: In this state, some bridge elements suffer from significant damage, classifying them as moderately damaged. This state could include failure or substantial movement in secondary structural elements (such as approach slopes, embankment fill, expansion joints, pavement, and backwalls) and visible cracks, minor residual deformations, spalling, misalignments, and other localized issues in primary structural elements. While the bridge's functionality may be temporarily influenced, it can be restored through appropriate repairs.
- **Damage State 4 (DS4)**: DS4 indicates severe damage. Load-bearing components such as connections, piers, abutments, and the bridge deck exhibits considerable deterioration. Scouring can compromise structural stability. Addressing this level of damage requires extensive reconstruction and intrusive repair techniques. This level of damage can significantly delay the bridge's operations.
- **Damage State 5 (DS5)**: Performance level is evaluated as near or total collapse. This state involves extensive damage to structural components, posing a high risk of structural failure or collapse. Major damage to structural members significantly weakens their load-bearing capacity, including issues like tilting of the substructure, foundation failure, and deck unseating. Repairing the entire bridge at this level is exceptionally challenging, time-consuming, costly, and frequently impractical.

DSs in Table 2 offer a method to assess structural damages in bridges, but also the socio-economic impact of the damage, ranging from fully operational (corresponding to DS1) to fully interrupted operation (corresponding to DS5).

Table 2. Proposed DSs along with socio-economic considerations.

Damage States	Overall Classification	Bridge components	Description	Repair	Socio-Economical Description
DS1	Null	Serviceability elements	Minor damage to small-scale detachment	No or cosmetic repair	Fully operational
		Secondary structural elements	Cosmetic damage to onset of movement of components		
		Primary structural elements	Barely visible cracking		
DS2	Minor	Serviceability elements	Major (or extreme) damage or total loss of some or all elements	Minor repair	Operation with caution
		Secondary structural elements	Moderate movement of components while remaining structurally stable		
		Primary structural elements	Clogging of bridge opening with partial effect on components, onset of minor cracking and spalling, and shallow scouring or slight erosion		
DS3	Moderate	Serviceability elements	N/A	Repair	Interim suspension
		Secondary structural elements	Total failure or major movement of approach slopes, embankment fill, expansion joints, pavement, and backwall		
		Primary structural elements	Clogging with major effect on components, cracking with minor residual deformations or spalling, initiation of local mechanisms, minor misalignment in super- or substructure components, minor movement at the connections, and moderate scouring around the pier with visible erosion or exposed piles not causing significant risk		
DS4	Heavy (Extensive or severe)	Serviceability elements	N/A	Major structural overhaul	Delayed operation
		Secondary structural elements	N/A		
		Primary structural elements	Major degradation in piers/columns without collapse, significant degradation in superstructure, significant misalignment of the abutment, substantial movement at the connections, and scouring with significant erosion and noticeable undermining in pier base posing risk for structural integrity		
DS5	Extreme (Near collapse or total collapse)	Serviceability elements	N/A	Rebuilt, repair may not be feasible	Closed
		Secondary structural elements	N/A		
		Primary structural elements	Total collapse or partial collapse of super- or substructure components, abutment failure, significant movement (or even loss) of connections, deck unseating, structural tilting, shallow/deep foundation failure, and extreme scour		

2.2 Application of the proposed DS definition

The proposed DS classification was applied to assess bridge conditions following September 2024 flood event in the Czech Republic. Through a comprehensive methodology integrating field surveys, reconnaissance mission, and photographic evidence of the flood, the standardized DS framework enabled a systematic evaluation of structural damage, ensuring consistency across multiple affected bridges (Figure 1-Figure 5).

Figure 1. DS1: Serviceability element damage

Figure 2. DS2: Bridge clogging

Figure 3. DS3: Scour in the abutment

Figure 4. DS4: Misalignment of abutment

Figure 5. DS5: Tilting of the superstructure caused by abutment failure

3 Conclusions

This study proposed a classification framework to systematically assess the extent of the bridge damage. The framework categorizes damage into five levels, considering the severity and impact on bridge functionality. The classification was applied in evaluating damage after a flood event in the Czech Republic stuck in September 2024, demonstrating its practicality in real-world scenarios.

The DS descriptions range from Minor Damage (DS1), which includes slight defects with no structural impact, to Complete Failure (DS5), where the bridge is no longer functional or safe. Moderate (DS2) and Heavy Damage (DS3) represent increasing deterioration affecting functionality and requiring maintenance. Severe Damage (DS4) includes major structural failures that compromise load-bearing capacity, necessitating immediate intervention.

This framework provided a structured method for assessing post-flood bridge damage, ensuring consistent classification and prioritization of repair needs. While damage thresholds differ across various literature sources, the approach proved effective for rapid condition evaluations during disaster response. Future research should focus on creating a risk assessment for bridges that may be at risk of flooding so that we can refine the prioritization of bridge repair before flood damage occurs.

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