

Performance-Based Seismic Assessment of Cable-Stayed Bridges with CFRP Stay Cables: A Critical Review

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ABSTRACT

Cable-stayed bridges are increasingly required to satisfy explicit post-earthquake functionality, repairability, and collapse-prevention objectives while extending span, durability, and service-life performance. Carbon-fiber-reinforced polymer (CFRP) stay cables are attractive because of their high specific strength, low self-weight, corrosion resistance, fatigue endurance, and reduced sag; however, their lower elastic modulus, brittle tensile failure, anchorage sensitivity, and limited full-scale seismic evidence complicate performance-based adoption. This review critically integrates several studies including non-linear seismic behavior of CFRP cables. The evidence is classified into CFRP cable mechanics and anchorage, structural-system response, deterministic nonlinear analysis, probabilistic demand and fragility, near-fault and spatially variable excitation, seismic control, validation, collapse, and life-cycle decision making. Quantitative comparisons show that CFRP density is approximately one-fifth that of steel, reported tensile strengths commonly exceed 2.0 GPa, and sag can be markedly reduced in long stays. Recent bridge studies report lower displacement, internal-force, and buffeting demands for selected CFRP or hybrid arrangements, while full-scale anchorage testing has reached 10.8 MN and multi-million-cycle qualification. Across seismic fragility studies, velocity-related intensity measures—particularly PGV or root-mean-square velocity frequently outperform PGA for long-period cable-stayed systems. Bearings, deck–tower interfaces, transition piers, lower pylon regions, and the longest stays repeatedly emerge as critical components. The principal gaps are the absence of full-scale CFRP bridge earthquake data, experimentally calibrated brittle cable/anchorage limit states, coupled deterioration–seismic models, standardized modelling protocols, and risk-consistent life-cycle optimization. A research framework is proposed that combines digital-twin model updating, multi-hazard nonlinear simulation, component testing, uncertainty propagation, and consequence-based design to support reliable CFRP cable-stayed bridge implementation.

Keywords: *Cable-stayed bridge; Carbon-fiber-reinforced polymer; Fragility analysis; Nonlinear time-history analysis; Performance-based seismic design; Seismic isolation; Spatially varying ground motion; Structural resilience*

1. INTRODUCTION

Cable-stayed bridges occupy a critical range between conventional girder systems and suspension bridges because their inclined stays efficiently transfer deck loads to slender pylons while retaining relatively high global stiffness. Their long natural periods, low inherent damping, strong geometric nonlinearity, and dependence on deck–pylon–cable interaction nevertheless make their seismic behavior fundamentally different from that of ordinary short- and medium-span bridges. Modern design therefore cannot be reduced to a single elastic force check. Performance-based seismic design (PBSD) requires a transparent chain from hazard intensity to engineering demand, component damage, system functionality, repair consequence, and acceptable risk [1]. Project experience on the Gerald Desmond Bridge illustrates how material strains, residual drifts, soil–structure interaction, and nonlinear response-history analysis can be tied to explicit performance objectives at multiple earthquake levels [2]. The introduction of CFRP stay cables changes this chain at both material and system levels. CFRP combines low density, high tensile strength, corrosion resistance, and strong

fatigue performance; these attributes reduce cable self-weight and sag and can increase the effective stiffness of very long stays even when the constituent elastic modulus is lower than that of steel [3], [4]. Xie et al. reported CFRP elastic moduli of approximately 137–159 GPa, tensile strengths of 2.02–2.55 GPa, density near one-fifth of steel, and an axial thermal expansion coefficient near $0.6 \times 10^{-6}/^{\circ}\text{C}$ [5]. Such properties alter the distribution of mass, cable frequencies, geometric stiffness, thermal force, bridge–cable coupling, and potentially the earthquake demand transmitted to pylons, bearings, and foundations.

Seismic assessment of CFRP cable-stayed bridges is not mature enough to support unqualified material substitution. Most existing bridge fragility research was developed for steel-stayed or conventional concrete/steel systems. It nevertheless provides the methodological foundation needed for CFRP implementation: uncertainty-aware component fragility [10], component-to-system aggregation [11], tall-pier and multi-pylon vulnerability [12], pulse-sensitive intensity measures [13], generalized demand models [14], and mountainous-site assessment [15]. These studies repeatedly show that vulnerability shifts between bearings, joints, pylon regions, transition piers, and long stays as the structural configuration and ground-motion family change. Consequently, a credible CFRP assessment must update not only cable properties but also modal characteristics, damping assumptions, damage states, correlations, replacement consequences, and interaction with control devices. Previous reviews have mainly emphasized FRP material properties, anchorage technology, static behavior, wind performance, or ultimate span [4]. Conversely, seismic reviews and state-of-practice papers have focused on conventional cable-supported bridges [1]. The intersection performance-based seismic assessment of cable-stayed bridges that use CFRP or steel–CFRP hybrid stay systems has not been synthesized with sufficient attention to component limit states, probabilistic demand, full-system fragility, validation, near-fault excitation, spatial variation, and life-cycle consequences. This review addresses that need.

The contributions of this paper are fourfold. First, it consolidates material-, component-, and bridge-level CFRP evidence with the established PBSD and fragility literature. Second, it compares the modelling choices that govern predicted performance: cable constitutive representation, sag correction, damping, deck–pylon connection, foundation model, ground-motion intensity measure, and component damage criteria. Third, it identifies where apparent agreement such as lower global response with lightweight cables does not automatically imply lower risk because brittle cable and anchorage capacities are less well calibrated than concrete or steel limit states. Fourth, it proposes a traceable research pathway from coupon and anchorage tests to validated digital twins, multi-hazard fragility, loss analysis, and code-ready design rules. The remainder of the paper presents the review protocol, theoretical background, thematic synthesis, author-wise comparison, cross-study critique, trends, gaps, future directions, practical implications, and conclusions.

2. FUNDAMENTAL CONCEPTS AND THEORETICAL BACKGROUND

2.1 Cable-stayed system mechanics and CFRP substitution

A cable-stayed bridge is an internally coupled system: the deck distributes gravity and lateral loads, the pylons provide vertical and transverse load paths, and the inclined stays act as tension-only supports whose axial stiffness depends on material modulus, area, initial tension, inclination, length, and sag. Direct replacement of steel cable by CFRP using equal area is generally inappropriate. Equivalent strength may reduce area because CFRP tensile strength is higher, whereas equivalent axial stiffness requires a larger CFRP area because its modulus is lower. The choice changes dead load, static geometry, modal properties, cable stress ratio, and cost [4], [6], [7], [8].

For a long cable, the secant or equivalent modulus may be represented by the Ernst-type expression

$$E_{eq} = \frac{E}{1 + \frac{\gamma^2 L_h^2 E A}{12 T^3}} \quad (1)$$

where E_{eq} is the equivalent axial modulus (Pa), E is the material modulus (Pa), γ is cable weight per unit volume (N/m^3), L_h is horizontal projected length (m), A is cable area (m^2), and T is cable tension (N). Equation (1) shows why low-density CFRP can retain much more of its material modulus in very long stays. In a 1500 m comparison, the longest steel stay retained only about 0.58 of its original modulus, whereas comparable CFRP stays showed reductions of only about 2–7% depending on the equivalence rule [8].

For a taut cable with negligible bending stiffness, the n th natural frequency can be approximated by

$$f_n = \left(\frac{n}{2L}\right) \sqrt{\frac{T}{\mu}} \quad (2)$$

where f_n is frequency (Hz), n is mode number, L is cable length (m), T is tension (N), and μ is mass per unit length (kg/m). The lower mass of CFRP increases cable frequencies and can reduce coincidence with global bridge modes [5]. This is beneficial for some parametric and buffeting responses but does not remove rain-wind, vortex, anchorage-bending, or local vibration concerns [8].

2.2 Probabilistic seismic demand and fragility

A conventional power-law PSDM is

$$\ln(EDP) = \ln(a) + b \ln(IM) + \varepsilon, \quad (3)$$

where IM is the ground-motion intensity measure, a and b are regression coefficients, and ε is a zero-mean residual with logarithmic standard deviation $\beta_{D|IM}$. For lognormal demand and capacity, the probability of exceeding damage state ds is commonly expressed as,

$$P[DS \geq ds | IM] = \frac{\Phi\{\frac{[\ln \hat{S}_D(IM) - \ln \hat{S}_{C,ds}]}{\sqrt{(\beta^2_{D|IM} + \beta^2_{C,ds})}}\}}{\sqrt{(\beta^2_{D|IM} + \beta^2_{C,ds})}} \quad (4)$$

where Φ is the standard normal cumulative distribution function; $\hat{S}_D$ and $\hat{S}_{C,ds}$ are median demand and median capacity; and $\beta_{D|IM}$ and $\beta_{C,ds}$ are dispersions. Component fragilities can be combined with serial, parallel, bounding, Monte Carlo, or joint-demand models to estimate system fragility [10].

IM selection is especially important for cable-stayed bridges because their long periods and multiple response mechanisms make PGA an incomplete descriptor. PGV repeatedly performs well for pulse-like and multi-pylon bridges [11], [13]–[15], [17]. Fault-crossing analysis identified root-mean-square velocity as the best of 12 candidates [16]. The correct conclusion is not that one velocity measure is universally optimal; it is that IM selection must be tested against the EDPs, motion family, hazard computability, and bridge period, with vector IM s used when a single scalar cannot represent pulse period, directionality, vertical motion, or spatial variation.

2.3 Life-cycle consequence and decision variables

A simplified present-value life-cycle cost is

$$LCC = C_0 + \frac{\sum_{t=1}^N C_t}{(1+r)^t} + E[L_H], \quad (5)$$

where C_0 is initial cost, C_t is maintenance or replacement cost in year t , r is the discount rate, N is the analysis horizon, and $E[L_H]$ is expected hazard loss including direct repair, downtime, user delay, and possibly casualties or network consequence. The value of CFRP is therefore coupled to seismic fragility, corrosion avoidance, inspection, replaceability, and traffic importance—not merely to cable price.

3. LITERATURE SURVEY

3.1 CFRP cable properties, anchorage, and engineering deployment

The CFRP literature develops along a clear hierarchy: material feasibility, anchorage, small bridge application, large cable qualification, and system integration. Meier's field-oriented review established the durability and specific-strength argument and documented early monitored use [3]. Yang et al. then showed that the bridge-level benefit is controlled by sag, equivalent modulus, fatigue, anchorage, shear/bending resistance, and economics rather than by tensile strength alone [4]. The material data synthesized by Xie et al. confirm the fundamental trade-off: CFRP is much lighter and stronger in tension than steel but less stiff and substantially less ductile [5]. Application studies close part of the gap between coupon data and structural use. The first Chinese CFRP cable-stayed bridge established practical procedures for bond-type anchorage, cable tensioning, and construction simulation. Experimental–numerical work later showed that finite-element models can reproduce the static and modal behavior of a small CFRP cable-stayed bridge and can be transferred cautiously to larger concepts. A major advance is the 10 MN-class stay application, where a 121-tendon cable achieved 10,805 kN capacity, exceeded its theoretical target, retained about 90% capacity after two million fatigue cycles, and was subjected to elevated-temperature qualification. This is important evidence for strength and anchorage robustness, but it is not equivalent to validation under multi-axial earthquake deformation.

Fatigue studies identify anchorage as the critical transition between favorable uniaxial material properties and system reliability. Feng et al. found that FRP cable fatigue can exceed steel under comparable safety-factor formulations. Full-scale anchorage testing showed progressive outer-tendon splitting and rupture, an 8% stiffness reduction after 1.2 million cycles at a 500 MPa stress range, and projected qualification for two million cycles below a 470 MPa design range. PBS models should use these observed mechanisms to define damage states rather than treating the cable as an indefinitely elastic truss. Critical synthesis: the evidence is strong for static tensile capacity, fatigue resistance, corrosion avoidance, and practical anchorage at selected scales. It is weak for post-damage residual capacity, combined axial–bending–shear demand at the anchor, rate effects, fire followed by earthquake, installation defects, and statistical capacity distributions. Those missing distributions directly limit fragility analysis.

3.2 Structural configuration, sag, dynamics, and hybrid material layouts

Long-span analyses broadly agree that low cable self-weight reduces sag and can improve dynamic separation between cable and bridge modes [5]. However, equivalent-strength and equivalent-stiffness substitutions produce different cable areas, stresses, and costs. Hybrid arrangements exploit this by placing CFRP or other FRP materials where long-cable sag and corrosion dominate and retaining stiffer or less expensive materials elsewhere. In the short-span bridge studied by Lu et al., the cable arrangement in the long-cable region produced meaningful differences under live, temperature, and earthquake loading; the preferred hybrid layout reduced maximum vertical girder displacement by 12% relative to the all-CFRP scheme and reduced selected force and displacement responses relative to steel. Figure 1 shows the bridge geometry and cable regions used for that comparison.

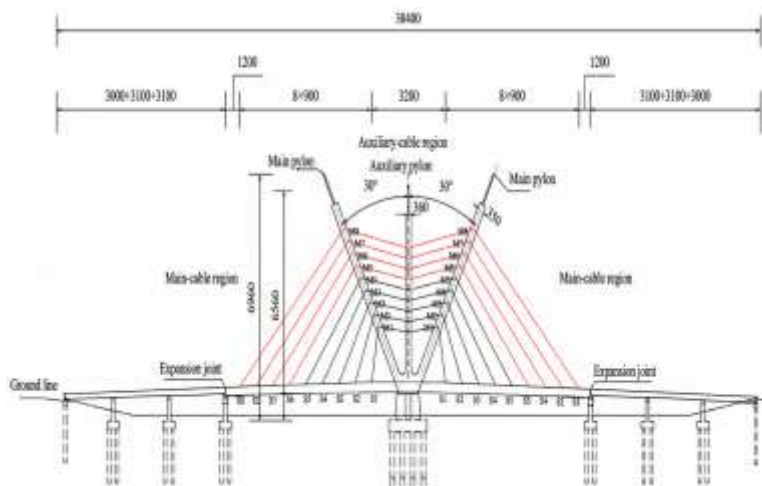


Figure 1. General layout and cable regions of the short-span steel–CFRP hybrid cable-stayed bridge. Ref. [7]

The design space expands further when CFRP stays are combined with UHPC or CFRP–UHPC girders. Ren et al. demonstrated the mechanical feasibility of a super-long-span concept. Tan et al. reported a 34.6% reduction in superstructure weight, a 30.9% increase in global stability safety factor, a 35.7% increase in initial cost, and a 21.3% reduction in 100-year life-cycle cost for an 1800 m concept. Figure 2 illustrates the proposed composite girder and nodal concept. These values are promising, but the earthquake performance depends on node ductility, local failure, fire, construction tolerance, and repairability—issues that global beam/truss FE models cannot resolve.

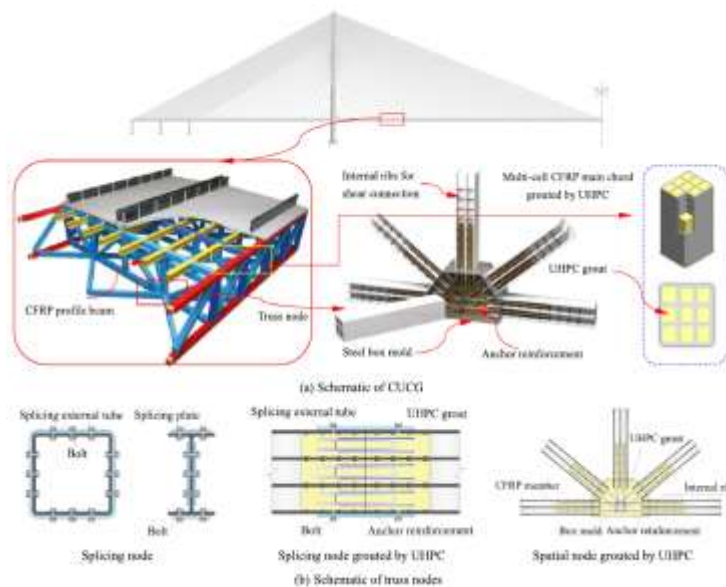


Figure 2. Concept of the CFRP–UHPC composite girder system for a super-long-span cable-stayed bridge.

Wind evidence is relevant to seismic design because the same mass, stiffness, and modal changes govern both hazards. Nie et al. found CFRP-scheme buffeting reductions of 12%, 14%, and 28% in vertical, torsional, and lateral directions, respectively, while also identifying vortex-induced vibration and anchorage-end bending as unresolved concerns [8]. Jaiswal et al. independently showed that cable area can be more influential than modulus in a conventional bridge parametric study [9]. Together, these results caution against describing CFRP substitution as a single material switch; it is a coupled optimization of area, prestress, layout, mass, equivalent modulus, and anchorage detail. Critical synthesis: the deterministic studies consistently favor lightweight long-cable applications, but many compare bridges with different implicit safety margins or equivalence rules. Future comparisons must enforce common reliability targets, geometric constraints, aerodynamic criteria, and damage capacities before declaring one material system superior.

3.3 Deterministic nonlinear response and performance criteria

PBSD practice for cable-supported bridges defines performance through allowable damage, strain, residual deformation, and service restoration [1], [2]. The framework is directly applicable to CFRP bridges, but its component criteria must be redefined. Current deterministic studies mostly compare peak displacement and internal force. Such indicators are necessary but not sufficient: a lower pylon moment does not prove lower risk if the cable or anchorage has a smaller deformation margin or if the new modal periods align with near-fault pulses. The choice of deck–pylon connection strongly controls response. Rigid connections restrain deck movement but amplify force transfer; floating systems reduce force while increasing displacement and pounding risk. Geometric configuration also matters. Fawzy et al. found pyramid and delta pylons more favorable within their response-spectrum comparison and found little effect of deck width on normalized shear for the studied inverted-Y cases. Because the analysis remained largely elastic, the finding should guide preliminary configuration rather than final performance ranking.

Deterministic nonlinear analysis remains indispensable for identifying load paths, sequence effects, cable force redistribution, and local response. It should be structured around performance checks: service continuity under frequent events; repairable, inspectable damage under design events; and controlled noncollapse under rare events. For CFRP stays, checks should include maximum and minimum cable force, anchor deformation, local bending, residual cable force distribution after one-stay damage, and accessibility for inspection or replacement.

3.4 Probabilistic demand, fragility, and risk

Fragility research provides the most transferable framework for CFRP PBSD. Pang et al. formalized modelling and record uncertainty [10]. Zhong et al. developed a component-to-system procedure and showed that PGV is often a more efficient IM than acceleration measures for long-span bridges [11]. Li et al. used 80 motions for a five-span tall-pier bridge and identified expansion joints, the deck, and cables as more vulnerable than tall piers [12]. Pulse-like motion studies and generalized regression further support velocity-related IMs and show that vector or combined IMs can improve fit [13], [14].

The vulnerable component is configuration-dependent. In a multi-pylon mountainous bridge, bearings and the longest cables were critical, whereas the super-high piers and pylons were comparatively robust [15]. Shaking-table fragility and medium-span system studies show the value of physical damage observations and component correlation. Offshore multi-support analysis demonstrates that spatially varying input can change component fragility and cannot be replaced by uniform excitation for long crossing structures.

Fault-crossing results are particularly instructive. Guo et al. generated synthetic fling-step motions, applied IDA, and selected root-mean-square velocity as the best IM. Transition-pier bearings were most vulnerable, transverse pylon fragility increased under fault crossing, and stay-cable vulnerability remained broadly comparable with the near-fault case [16]. The reproduced fragility comparisons in Figure 3 show why a single statement such as “cables are safe” is insufficient: different damage states and components diverge as intensity increases.

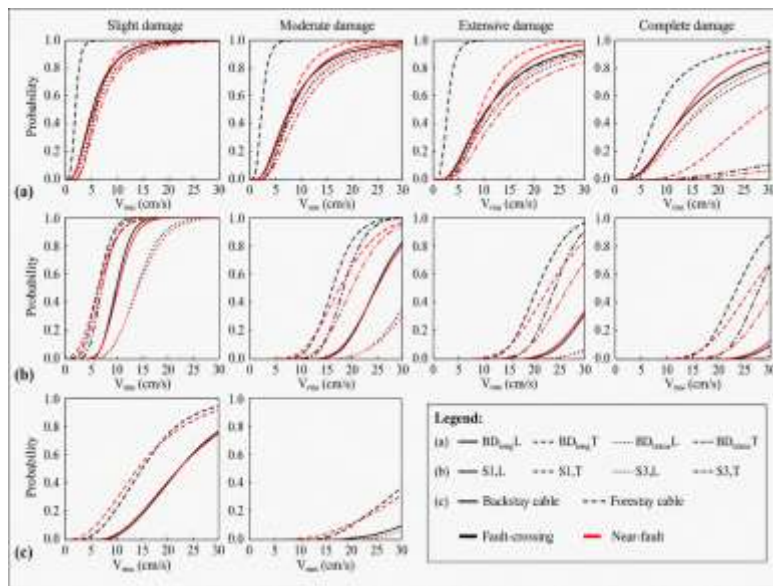


Figure 3. Component fragility comparison for fault-crossing and near-fault cable-stayed bridges. Ref. [16]

Critical synthesis: fragility models are mature for conventional pylon, pier, and bearing EDPs, but not for CFRP-specific cable and anchorage damage. Most studies use stress-ratio thresholds or elastic cable assumptions. A CFRP bridge fragility model should propagate uncertain tensile/anchorage capacity, bending-induced reduction, degradation, load redistribution, and correlation among stays.

3.5 Near-fault, fault-crossing, spatial variability, and foundation effects

Near-fault pulses are dangerous for cable-stayed bridges because pulse periods can approach long global periods. Bidirectional analysis of a 432 m main-span bridge showed that near-fault records produce larger response than paired far-field records and that directionality is more pronounced near faults. The percentage and simplified SRSS combination rules were not reliable substitutes for explicit bidirectional time histories in that study. Site and support variability can either amplify or reduce response depending on apparent wave velocity, span, and modal phase. Gao et al. modelled a bridge with a 216.4 m tower and approximately 105 m piles; softer support sites produced about 1.35 times the response of stiffer conditions, and greater differential soil conditions produced ratios up to 1.75, while deep-water and sediment effects were less influential for the studied configuration. Tian and Lou explained the nonmonotonic dependence on wave speed as traveling-wave resonance. Multi-shake-table experiments and calibrated numerical analysis confirm that asynchronous support motions are not a purely theoretical issue.

Pounding and unseating become important when isolation or floating connections increase movement. Gao et al. found that friction pendulum bearings and fluid viscous dampers reduce pounding between main and approach bridges, but low apparent wave velocity and near-fault pulses can still amplify impact. The implication for CFRP systems is indirect but important: lightweight superstructures may reduce inertia, yet connection movement and device compatibility must be assessed explicitly. Critical synthesis: no reviewed study jointly considered CFRP stay damage, near-fault pulse directionality, spatially variable support input, nonlinear SSI, pounding, and deterioration. Current conclusions therefore represent isolated slices of the multi-hazard problem.

3.6 Seismic isolation, energy dissipation, and low-damage systems

The control literature shows that device location and parameter selection are as important as device type. The Shipshaw retrofit study compared five configurations and found that isolation distributed at supports and deck–tower interfaces improved both longitudinal and transverse response, whereas partial schemes could improve only one direction. Related analysis showed the expected force–displacement trade-off: isolation increased a representative deck displacement from 5.8 to 12.4 cm while reducing force demand. Single-concave friction-pendulum analysis reached similar conclusions for the Manavgat Bridge. Self-centering systems are attractive because residual displacement is a PBSD decision variable. Li et al. modelled 54 SMA roller bearings and compared floating, rigid, and SMA-isolated systems. PGV was the best tested IM; the SMA system had the lowest system fragility, and pier, tower, and cable collapse probabilities remained below 1.5% at PGV=10 m/s in the studied models [37]. Their component-to-system workflow is reproduced in Figure 4. Shaking-table testing of SMA dampers also demonstrated substantial reductions in relative deck displacement and tower response.

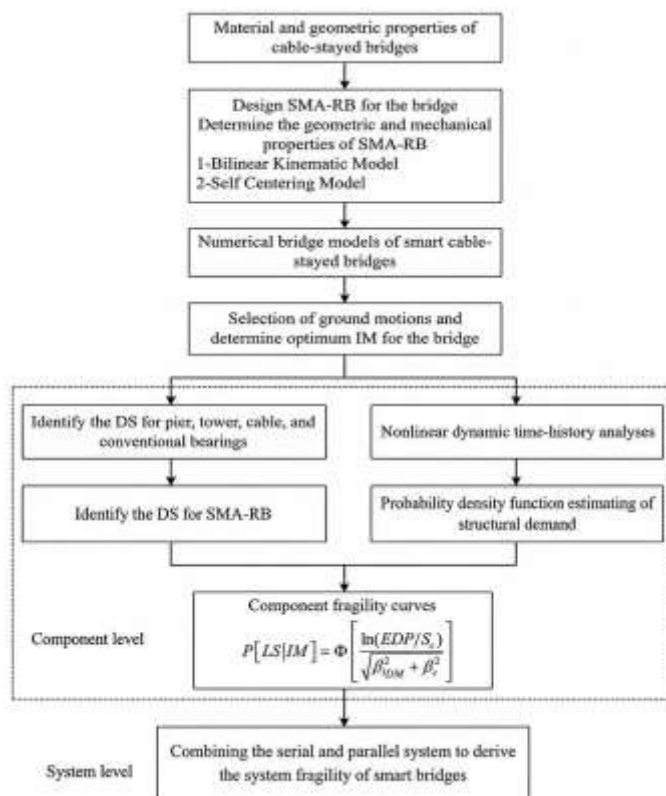


Figure 4. Component- and system-level fragility workflow for a cable-stayed bridge with SMA roller bearings. Ref. [17]

PBSD optimization improves on trial-and-error device selection. Wen et al. combined multiple-stripe analysis, component fragility, repair-cost surfaces, and a genetic algorithm to optimize viscous and metallic dampers. Optimal devices reduced expected repair cost, but poorly selected parameters could worsen some responses. Benchmark studies of negative-stiffness, hybrid passive–semi-active, magnetorheological, and hysteretic systems established reproducible comparison metrics and highlighted the effect of limit-state definitions. Elastic restraint tests provide another low-cost option, although response reduction was record-dependent.

Critical synthesis: control studies generally use steel-stayed benchmark bridges. CFRP changes superstructure mass, cable frequency, force distribution, and possibly damping. Device properties optimized for a steel-stayed bridge should therefore be re-optimized rather than transferred unchanged.

3.7 Life-cycle sustainability and decision making

Life-cycle cost evidence supports CFRP most strongly when spans are long, replacement disruption is large, and the bridge carries high-value traffic. Hybrid FRP arrangements can improve economic efficiency by reserving premium material for the most beneficial cable regions [6]. The 1800 m CFRP–UHPC concept shows how lower maintenance and structural weight can overcome higher first cost over 100 years. These studies, however, depend on deterministic

maintenance schedules and assumed unit prices. A complete PBS decision model should multiply hazard occurrence by damage, downtime, traffic consequence, environmental burden, and repair feasibility.

Critical synthesis: sustainability analysis is not yet coupled tightly to fragility. The next generation of studies should report expected annual loss, downtime distribution, carbon embodied in replacement, inspection demand, cable recycling/end-of-life, and network resilience for steel, CFRP, and hybrid alternatives under a common hazard model.

4. COMPARATIVE REVIEW

Table 1 demonstrates that CFRP stay-cable research has progressed from conceptual feasibility and field demonstrations to advanced numerical modelling, full-scale qualification, fatigue testing, hybrid optimisation, and life-cycle assessment. Early studies established the principal advantages of CFRP, including approximately one-fifth the unit weight of steel, tensile strength between 2.02 and 2.55 GPa, high corrosion resistance, and reduced vibration susceptibility. Numerical investigations on 1400–2038 m bridges indicated that CFRP and hybrid FRP systems can maintain acceptable global stiffness while reducing sag, seismic response, and selected wind-induced effects. Experimental anchorage studies further strengthened practical confidence: only 8% stiffness reduction was reported after 1.2 million cycles at a 500 MPa stress range, while 2 million cycles were considered feasible below 470 MPa. Full-scale testing of a 10 MN-class CFRP stay achieved 10,805 kN capacity against a theoretical value of 10,710 kN and retained approximately 90% strength after fatigue exposure.

Table 1. CFRP Cable Materials, Anchorage, Bridge Configuration, Dynamics, And Life-Cycle Studies.

Ref.	Method / software	Model, material, dimensions / key inputs	Loading / test conditions	Outputs and major quantitative results	Key contribution	Limitations
[1]	State-of-practice review	Recent US cable-supported bridges; deformation-based checks	Multiple hazard levels; nonlinear response history analysis	Material strains, residual drift, global performance	Links local deformation limits to global objectives	Not a CFRP-specific validation study
[2]	Project case; nonlinear time-history + SSI	Cable-stayed bridge in active near-fault region	Evaluation earthquakes ; detailed SSI	Strain and residual drift compliance	Project-level implementation of explicit performance criteria	Single project; proprietary modelling details limited
[3]	Critical review + monitored field applications	Stork Bridge: 124 m overall; 2 CFRP stays among 24	Service and fatigue exposure	Cable durability, anchorage, monitoring	Establishes practical pedigree and anchorage concept	Limited seismic quantification
[4]	Review + analytical comparisons	Steel, CFRP, BFRP and hybrid FRP cables	Static, dynamic, fatigue, wind and economic conditions	Sag, equivalent modulus, span and durability	FRP theoretical span 2.83–4.78 times steel; CFRP sag <17% of steel at 1400 m	Highlights lack of full-scale seismic and standardization data

Ref.	Method / software	Model, material, dimensions / key inputs	Loading / test conditions	Outputs and major quantitative results	Key contribution	Limitations
[5]	3D numerical static/dynamic analysis	1400 m cable-stayed bridge; CFRP E 137–159 GPa	Dead/live, wind, traffic and vibration	Displacement, modal frequency, cable vibration	CFRP weight $\approx 1/5$ steel; tensile strength 2.02–2.55 GPa; lower cable vibration	Brittle material behavior and anchorage not modelled in damage states
[6]	Analytical parametric + FE + LCC	2038 m sea-crossing bridge	Static, wind, seismic and life-cycle costs	Deflection, stability and LCC	Hybrid FRP arrangement satisfies static limits and improves seismic/wind response	Material price and durability assumptions dominate economics
[7]	3D FE parametric study	384 m overall short-span highway bridge; four cable patterns	Dead, live, temperature and seismic loads	Girder/tower displacement, force, stability	Hybrid arrangement reduced max vertical displacement 12% versus all-CFRP and improved seismic response versus steel	Single bridge and deterministic input
[8]	FE aeroelastic assessment	1500 m bridge schemes	Mean wind, buffeting, flutter and vortex excitation	Deflection, buffeting, resonance, bending angle	CFRP buffeting 12%, 14% and 28% lower vertically, torsionally and laterally	Vortex-induced vibration and anchorage-end bending remain concerns
[9]	MIDAS Civil parametric analysis	420 m three-span fan bridge	IRC loading; cable area $\pm 5\text{--}20\%$; modulus varied	Girder/tower force and displacement	Cable area changes had greater influence than modulus changes	Conference-series article; no nonlinear seismic validation

The evidence also reveals important trade-offs. CFRP systems generally involve higher initial costs, brittle tensile behaviour, anchorage complexity, limited ductility, and insufficient full-scale seismic validation. Nevertheless, life-cycle studies show that reduced replacement, rehabilitation, and user-disruption costs can offset the initial premium, particularly for 1200–1800 m spans. Recent CFRP–UHPC concepts achieved 34.6% lower structural weight, 30.9% higher stability, and 21.3% lower 100-year cost, despite a 35.7% increase in initial expenditure. Overall, CFRP cables

are technically promising, but broader adoption requires validated nonlinear damage models, standardised design provisions, environmental durability data, and long-term field monitoring.

Table 2. Probabilistic Demand, Intensity-Measure, And Fragility Studies

Ref.	Method / software	Model, material, dimensions / key inputs	Loading / test conditions	Outputs and major quantitative results	Key contribution	Limitations
[10]	Nonlinear FE + uncertainty sampling	Representative cable-stayed bridge	Multiple ground motions and material/model variables	Component/system fragility	Formalizes uncertainty sources for long-span bridge fragility	Limit-state data remain model-dependent
[11]	OpenSees + Monte Carlo	Typical long-span Chinese cable-stayed bridge	Nonlinear histories; material and record uncertainty	Pylon, bearing, cable and system fragility	PGV selected as optimal; system fragility close to upper bound under low demand correlation	Generic bridge; limited field calibration
[12]	OpenSees; 80 records	Five-span cable-stayed bridge with tall piers	Longitudinal nonlinear histories	Deck, joint, cable, pier and system fragility	Expansion joint, deck and cables more vulnerable than piers	Longitudinal direction emphasized
[13]	PSDM using 121 recorded + 121 artificial pairs	Long-span cable-stayed bridge	Pulse-like near-fault motions	Efficiency, sufficiency and EDP dispersion	PGV best overall; lower pylon regions most vulnerable	Pulse simulation and selected bridge limit generality
[14]	Generalized linear/Lasso regression	672 m main + 324 m side spans	Far-field and near-fault records	EDP-IM fit, efficiency and sufficiency	PGV strong single IM; combined IMs improve prediction	Model selection may not transfer to other periods/sites
[15]	Nonlinear FE; 16 IMs	Three pylons; spans 249.5+550+550+249.5 m; 264 cables	Scaled ground motions	Bearing, cable, pier and pylon fragility	PGV optimal; bearings and longest cables vulnerable	Single bridge; vertical/spatial input limited
[16]	OpenSees Py + IDA; 150 synthetic motions	Cable-stayed bridge crossing vertical strike-slip fault at 90°	Fling-step and velocity-pulse motions	Bearing, pylon and cable fragility; 12 IMs	Vrms optimal; transition-pier bearings most vulnerable; transverse pylon capacity shifts 8–13%	One fault mechanism and crossing angle

Table 2 shows that probabilistic seismic assessment of cable-stayed bridges has evolved from basic uncertainty propagation to advanced component–system fragility, intensity-measure selection, shaking-table validation, and

spatially variable ground-motion analysis. Across several bridge configurations, nonlinear finite-element modelling, Monte Carlo simulation, incremental dynamic analysis, and probabilistic seismic demand models were the dominant approaches. Peak ground velocity repeatedly emerged as the most efficient single intensity measure for conventional and near-fault cases, whereas root-mean-square velocity performed better for fault-crossing bridges. The reviewed studies consistently identified bearings, expansion joints, decks, long stay cables, and lower pylon regions as the most vulnerable components, while tall piers were often comparatively less critical. Spatial variation, wave passage, site effects, and pulse-like motions significantly altered demand and fragility estimates, confirming that uniform excitation may underestimate risk. However, most conclusions remain bridge-specific because of limited field calibration, simplified fault mechanisms, uncertain component capacities, restricted loading directions, and insufficient transferability across different structural periods and site conditions.

5. FUTURE RESEARCH DIRECTIONS AND PRACTICAL IMPLICATIONS

Future research should focus on experimentally validated, multi-scale characterization of CFRP cables and anchorage systems. Experimental investigations should progress from material coupons and individual tendons to full anchorage assemblies and bridge subcomponents under axial tension, cyclic loading, imposed end rotation, temperature fluctuations, moisture, salt exposure, manufacturing tolerances, and fatigue damage. The resulting data should be incorporated into probabilistic limit-state models and residual-capacity relationships for nonlinear seismic fragility and resilience analyses. In parallel, newly constructed CFRP cable-stayed bridges should be equipped with structural health monitoring systems, including cable-force sensors, accelerometers, displacement transducers, temperature sensors, and distributed strain sensing. Integrating these measurements with Bayesian digital twins can reduce modelling uncertainty, quantify ageing effects, and enable rapid post-earthquake condition assessment.

At the structural level, future studies should optimize steel, CFRP, and hybrid cable systems based on reliability, life-cycle cost, downtime, carbon emissions, aerodynamic performance, and resilience rather than equivalent strength alone. Numerical simulations should incorporate realistic multi-hazard scenarios, including near-fault ground motions, vertical excitation, asynchronous support movement, soil–structure interaction, scour, hydrodynamic forces, pounding, wind loading, temperature variations, and cable loss. Fragility models should also consider correlated component failures, progressive cable rupture, load redistribution, repair duration, and restoration of traffic functionality. Hybrid experimental testing, open benchmark models, standardized reporting, climate-sensitive life-cycle assessment, and reliability-based code calibration are essential for translating research outcomes into practical design guidelines.

From an industrial perspective, the review demonstrates that CFRP cables are particularly advantageous for long-span bridges exposed to aggressive environments, where corrosion resistance, fatigue durability, reduced self-weight, and lower sag provide significant long-term benefits. Designers should clearly define cable-force calibration procedures, account for geometric nonlinearity and cable sag, and evaluate cable–anchor deformation instead of relying solely on tensile strength. Bridge owners and project managers should require traceable material properties, full-scale anchorage qualification, fire and fatigue verification, installation quality control, and long-term structural health monitoring as part of procurement specifications. Although CFRP cables involve higher initial costs, their economic viability should be assessed using life-cycle cost analysis that includes maintenance, inspection, traffic disruption, replacement, and hazard-related losses.

Manufacturers should prioritize consistent cable–anchorage capacity, standardized termination systems, durable protection methods, and reliable acceptance testing to minimize design uncertainty and improve industry confidence. Researchers should publish reproducible bridge-scale models linked to experimentally observed failure mechanisms and perform comparative evaluations of steel, CFRP, and hybrid cable systems under equivalent performance objectives. Policymakers and standards organizations should support pilot bridge projects accompanied by long-term monitoring and data-sharing initiatives while developing performance-based design provisions that specify minimum qualification tests, monitoring requirements, and independent verification procedures. Such an integrated research-to-practice framework will accelerate the safe, reliable, and economically sustainable implementation of CFRP cable systems in future seismic-resistant bridge infrastructure.

7. CONCLUSIONS

This review establishes that CFRP and steel–CFRP hybrid stay systems are promising for performance-based seismic design of cable-stayed bridges, where long spans, aggressive exposure, and high traffic-disruption costs govern material

selection. CFRP density is one-fifth that of steel, while tensile strengths exceed 2.0 GPa, allowing reductions in cable self-weight and sag. Full-scale qualification has reached the 10 MN class, with a measured capacity of 10,805 kN against a theoretical value of 10,710 kN, while fatigue studies reported only 8% stiffness loss after 1.2 million cycles at a 500 MPa stress range. At bridge level, hybrid cable layouts reduced vertical displacement by 12%, and a 1500 m bridge study reported buffeting reductions of 12%, 14%, and 28% in vertical, torsional, and lateral directions, respectively. A super-long-span CFRP-UHPC concept achieved 34.6% lower structural weight and a 30.9% higher global stability factor, although initial cost increased by 35.7%; however, projected 100-year cost was 21.3% lower. Seismic studies showed that PGV outperformed PGA as an intensity measure, whereas root-mean-square velocity was more effective for fault-crossing cases. Softer support conditions increased response by about 1.35 times, and stronger site contrasts produced increases up to 1.75 times. Despite these advantages, brittle failure, anchorage sensitivity, limited full-scale earthquake validation, and incomplete multi-hazard modelling remain major barriers. Future adoption should rely on probabilistic cable-anchor limit states, multi-support nonlinear analysis, monitoring-based digital twins, system fragility, and reliability-based life-cycle optimisation.

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