

Structural Health Monitoring and Active Cooperative Control of Frame Structures for Rapid Post-Earthquake Restoration

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Abstract—Rapid restoration after an earthquake depends on more than estimating whether a building avoided collapse. A usable decision process must distinguish residual deformation from repairable damage, integrate imperfect observations, and coordinate structural actions without displacing the responsible engineer's inspection and safety-evaluation role. Existing structural health monitoring systems commonly diagnose response or damage after an event, whereas repairable-frame systems commonly localize damage or reduce residual drift. Active and semi-active control studies, in turn, usually optimize peak response during excitation. The operational link between these three capabilities remains under-specified. This paper develops an original, human-supervised framework that connects structural health monitoring, a repairable moment-frame/rocking-core configuration, and constrained cooperative restoration control for rapid post-earthquake recovery. The framework fuses protected-zone strain, acceleration, displacement, and tendon-force measurements into a state estimate; classifies the inferred state into inspection, recoverable-damage, or escalation states; and selects a governed sequence of fuse release, self-centering action, and limited actuation. A six-storey analytical benchmark is used solely to make the equations, decision logic, figures, and data files reproducible. It is not a field dataset, a physical test, or a claim of validated building performance. In the prescribed benchmark, the closed-form restoration demand falls from 1.19 MN • m with locked fuses to 0.41 MN • m after staged fuse release, and becomes zero after the specified cooperative sequence supplies sufficient core restoring capacity. The principal contribution is therefore methodological: a transparent interface between monitoring evidence, restoration actions, and human safety decisions. The paper also defines sensing, latency, uncertainty, actuator, and inspection constraints that must be satisfied before such a framework can progress from analytical design to real-time hybrid testing and field deployment.

Keywords—structural health monitoring, active cooperative control, rapid post-earthquake restoration, repairable steel frames, residual drift, digital twin

I. INTRODUCTION

Earthquake engineering has historically treated survival, damage assessment, repair, and reoccupation as sequential but partially disconnected activities. Contemporary seismic loading and existing-building standards provide credible life-safety and assessment baselines [1] [2] [3], yet a building that remains standing can still be unusable because residual drift, damaged connections, nonstructural failures, inspection

delays, or restricted access interrupt recovery. This distinction has become central to resilience practice. Post-disaster safety-evaluation guidance separates a preliminary judgment of occupancy from the engineering work needed to determine repair scope, while functional-recovery guidance explicitly calls for shorter and more reliable routes to reoccupation [4] [5] [6]. For a frame structure in an urban recovery context, the relevant question is therefore not only whether collapse was prevented, but whether the damage state can be diagnosed, bounded, and converted into a safe, auditable restoration plan.

Structural health monitoring (SHM) can improve this decision process because it transforms structural response into evidence about condition. Vibration-based methods, image-based inspection, and learning-based classifiers have expanded the observable information available after earthquakes [7] [8]. Sparse acceleration measurements can support rapid estimates of interstorey drift in numerical studies of steel buildings [9], while unmanned aerial vehicles and building-information models can connect visible damage to individual components in a digital representation [10]. These capabilities are valuable, but an SHM estimate alone does not authorize reoccupation. Dynamic properties can vary with temperature, occupancy, sensor noise, soil – structure interaction, and model-form error. Any monitoring-informed decision must therefore retain uncertainty, record data quality, and route ambiguous cases to inspection rather than treating a classifier as an autonomous safety placard [8] [4].

In parallel, repairable and self-centering systems have altered the physical basis for recovery-oriented design. Replaceable steel links and fuses can concentrate inelastic demand in parts intended for inspection and replacement [11]. Self-centering moment frames, rocking columns, and hybrid connections can reduce residual deformation and preserve a clearer load path for repair [12] [13] [14] [15]. Functional-recovery analyses of steel moment frames further indicate that post-yield stiffness, residual drift, and reparability influence the time and consequences of recovery [16] [17]. Their loss and repair-consequence assumptions are commonly represented through the FEMA P-58 methodology [18]. Nevertheless, a repairable configuration does not by itself determine the condition of the as-built system after a specific earthquake, nor does it prescribe a safe sequence for releasing damaged components, applying restoring force, or verifying that the structure has responded as expected.

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Active and semi-active control create a third capability: deliberate modification of structural response within specified force, displacement, velocity, and power limits. Recent studies demonstrate delay-aware active-tendon control, active tuned-mass control, adaptive variable-stiffness control, semi-active damping, and observer-based strategies [19] [20] [21] [22] [23]. Real-time hybrid testing has also clarified that sensor synchronization, actuator delay, command compensation, and interface stability are not secondary implementation details [24] [25]. Yet much of this literature evaluates peak drift or acceleration during shaking. The post-event interval presents a different control problem. The structure may already contain residual deformation and damaged energy-dissipating components; the action must remain reversible, transparent, and subordinate to an inspection and repair workflow. A controller optimized solely for a response metric is inadequate if it conceals uncertainty, commands a damaged mechanism, or bypasses the responsible engineer.

This paper addresses that gap by formulating a human-supervised, closed-loop framework for frame structures designed with a repairable moment frame, a self-centering rocking core, protected sensing locations, and restoration actuators. The purpose is not to claim a deployable autonomous recovery system. Rather, the purpose is to establish a reproducible method that connects four tasks: (i) infer a bounded post-event state from heterogeneous sensor data; (ii) distinguish safety and recoverability decisions; (iii) allocate restoration actions across replaceable fuses, the restoring core, and limited actuation; and (iv) preserve traceability through an auditable digital repair record. The method concentrates on regular, low- to mid-rise steel frame archetypes with intentionally replaceable components. It does not model local connection fracture, nonstructural-component repair, lifeline restoration, or legal placarding as if they could be decided by the algorithm.

The paper makes three contributions. First, it defines an explicit architecture in which monitoring, digital-twin state estimation, human review, and controlled restoration share a single decision chain. Second, it derives a transparent restoration-demand balance and a constrained cooperative-control objective that expose the role of residual fuse resistance, $P - \Delta$ effects, core restoring capacity, and actuator limits. Third, it provides a deterministic six-storey analytical benchmark, editable tables, high-resolution figures, and CSV inputs so that the logic can be independently inspected. Table I summarizes the research questions and the associated evidence boundary. The remainder of the paper reviews the relevant literature, presents the method, documents the analytical data, reports the deterministic calculations, discusses applicability and limitations, and concludes with a staged validation agenda.

TABLE I. RESEARCH QUESTIONS, METHOD OUTPUTS, AND DECISION BOUNDARIES.

Research question	Method response	Primary output	Decision boundary
RQ1: Condition inference	Which measurements and uncertainty checks are required to estimate a repair-relevant residual state?	State estimate with drift, fuse, tendon, and data-quality variables	SHM prioritizes evidence; it does not assign a legal safety placard.

Research question	Method response	Primary output	Decision boundary
RQ2: Recoverability	When may a damaged frame enter a controlled restoration workflow?	Conservative classifier with inspection and escalation branches	Only designated repairable mechanisms are considered.
RQ3: Action allocation	How can fuse release, core restoration, and actuation be coordinated?	Constrained cooperative optimization and moment balance	Commands remain subject to force, travel, velocity, and authorization limits.
RQ4: Traceability	How can the process remain auditable for engineering review?	Versioned digital repair record and verification after every action	Documentation does not replace field inspection or authority requirements.

II. RELATED WORK

The first body of related work concerns post-earthquake SHM and damage-state inference. Deep-learning reviews classify the field into vibration, vision, and hybrid pipelines, but they also show that reported performance often depends on data composition, damage labels, and environmental normalization [7] [8]. For rapid assessment, sparse-response approaches are attractive because they reduce instrumentation burden. Tsuchimoto and co-workers used sparse acceleration measurements and nonlinear numerical models to infer safety-relevant drift in a five-storey steel building [9]. Portfolio-scale image recognition and remote sensing can extend triage across many buildings [26] [27]. These methods support prioritization; however, they do not resolve all uncertainty at the component scale. A frame may exhibit small global drift while a connection, cladding system, or utility remains impaired. The framework developed here treats monitoring as a source of evidence for a state estimate, not as a replacement for inspection.

Digital-twin research provides a suitable integration layer for that evidence. A post-earthquake digital twin can associate images, point clouds, measured response, component identifiers, design records, and inspection notes [10] [28]. The important methodological implication is that a state estimate should be time-stamped and versioned. Each update must retain the observations, model assumptions, confidence bounds, and decision rule that produced it. This is especially important when the state feeds a control decision: a command should be reproducible from the recorded evidence. Sensor placement is likewise not a matter of installing the greatest possible number of devices. It is an observability and optimization problem involving anticipated failure mechanisms, access, redundancy, failure of instrumentation, and the information value of each channel [29].

The second body of work concerns repairable, self-centering, and residual-drift-limited seismic systems. Performance-based design of SMA-bolted self-centering moment frames has shown that residual deformation can be a direct design target rather than an incidental outcome [12]. Repairability-based methods for steel moment frames with self-centering connections formalize peak displacement and residual displacement as complementary indicators [13]. Experimental work on replaceable links demonstrates that

carefully detailed steel fuses can sustain stable hysteresis while concentrating deformation in components intended for replacement [11]. Hybrid self-centering frames and rocking-column systems further combine energy dissipation with restoring mechanisms [14] [15]. These studies motivate the physical configuration selected here: a ductile frame absorbs demand in replaceable locations, while an elastic or near-elastic core supplies a recoverable restoring path.

Functional recovery cannot be inferred from residual drift alone. Probabilistic analyses have linked self-centering systems to repair time, repair cost, reoccupancy, and functional recovery, but they also show the importance of nonstructural inventories and recovery assumptions [16]. Analyses of special moment frames similarly report that enhanced post-yield stiffness can reduce residual drift and improve recovery, subject to the selected fragilities and ground motions [17]. Life-cycle studies indicate that partial self-centering may yield attractive benefits when initial cost, demolition thresholds, acceleration-sensitive contents, and repair consequences are considered together [30]. Accordingly, the present study does not translate a residual-drift value directly into a recovery time. Instead, it treats residual drift as one bounded structural input to an inspection, repair, and reoccupation decision process.

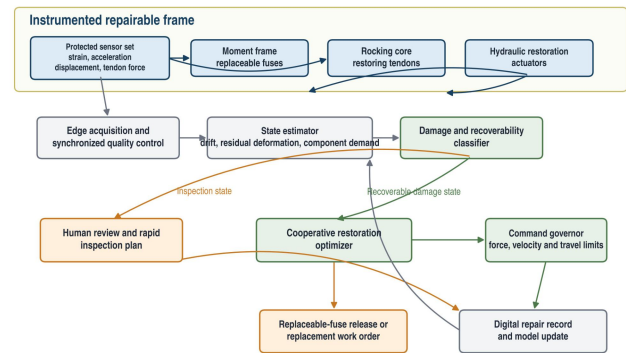
The third body of work concerns real-time control. Time delay, actuator saturation, and multi-input coordination can materially change an active-control result [19]. Variable-stiffness approaches with prediction seek to compensate for delay in sensing, computation, and device response [22]. Semi-active devices are attractive because their passive mechanical behavior can offer a fallback mode when active power or communication is unavailable [21]. Observer-based control can reduce computational burden while preserving explicit stability conditions [23]. Real-time hybrid simulation provides a technical pathway for testing these issues because it exposes time integration, actuator dynamics, measurement noise, synchronization, and stability at the physical-numerical interface [24] [25]. However, these contributions have rarely been combined with a controlled post-event repair sequence for a damaged, repairable frame.

A synthesis of the literature identifies four unresolved interfaces. First, damage detection is often separated from the decision logic that determines whether physical intervention is permissible. Second, repairable structural details are seldom connected to a sensor plan that specifically observes their condition before release or replacement. Third, active-control studies typically prioritize in-event response, rather than residual-state management under human supervision. Fourth, recovery studies may quantify time or loss without specifying how a measured post-event state drives a governed structural action. The proposed framework addresses these interfaces by placing diagnosis, classification, command governance, work orders, and model update in one traceable loop. It adopts the recovery orientation of current guidance [4] [5], the monitoring logic of SHM literature [7]–[10] [26]–[29], the physical reparability of self-centering and replaceable systems [11]–[17] [30], and the delay-aware constraints highlighted by control research [19]–[25] [31].

III. METHODS

The method follows a design-led analytical strategy. A repairable frame is first parameterized so that damage is intended to localize in replaceable fuses and the rocking core

remains available as a restoring mechanism. The structural configuration then determines the monitoring plan: sensors are installed at protected zones where their measurements are interpretable with respect to the intended mechanism. Next, a state estimator converts synchronized sensor streams into bounded estimates of global drift, residual deformation, fuse demand, tendon force, and data quality. A classifier converts those estimates into an operational decision state. Only the recoverable-damage state permits the controller to propose a restoration sequence; inspection, uncertainty, or escalation states divert the process to human review. The sequence is checked by a command governor that enforces travel, force, velocity, tendon-force, and uncertainty constraints. Figure 1 presents this architecture. Its central design principle is that data govern diagnosis, diagnosis constrains restoration, and inspection remains a mandatory human decision point.



Data govern diagnosis; diagnosis constrains restoration; inspection remains a mandatory human decision point.

Fig. 1. Human-supervised architecture for structural health monitoring and cooperative post-earthquake restoration. Sensors update a bounded state estimate; the classifier separates inspection from recoverable-damage paths; the command governor constrains any approved structural action.

The physical archetype combines three subsystems. The first is a steel moment-resisting frame whose beam-end zones contain replaceable energy-dissipating fuses. The second is a rocking core with tendons or an equivalent restoring device intended to remain within a controlled reserve. The third is a limited restoration-actuation system, represented here as hydraulically driven devices capable of imposing a slow, bounded return action after the earthquake has ceased. The actuator is not assumed to resist seismic actions autonomously. Its role is post-event: it may assist a verified restoration sequence, stop when a constraint is approached, and hand back to inspection when sensing quality degrades. This separation avoids conflating dynamic earthquake control with static or quasi-static post-event realignment.

Let the reduced structural state at time

$$kbex_k = [u_k, \dot{u}_k, q_f, k, T_c, b_k]^T \quad (1)$$

where u is the interstorey displacement vector, $\dot{u}$ is velocity, q_f is a vector of fuse demand variables, T_c is tendon force, and b denotes slowly varying model-bias terms. The measurement vector y_k contains acceleration, displacement, strain, tendon-force, and quality-control channels. The estimator uses the nonlinear observation model

$$y_k = h(x_k, \theta) + v_k \quad (2)$$

where θ is the current digital-twin parameter set and v_k is measurement error. Rather than treating the estimate as exact, the framework retains a covariance or interval

descriptor Σ_k . A practical implementation could use an extended Kalman filter, an ensemble method, or a constrained moving-horizon estimator. The analytical benchmark does not select one estimator; it specifies the data interfaces and the decision variables that any validated estimator must report.

The principal outputs are the residual drift ratio ϕ_{res} , the maximum interstorey drift ϕ_{max} , a fuse condition vector d_f , a normalized tendon-force reserve r_T , an observability score o , and an uncertainty index ξ . For fuse j , a normalized condition indicator can be written as $d_{f,j} = \min(1, |\varepsilon_j| / \varepsilon_{lim,j})$, where ε_j is measured or estimated strain and $\varepsilon_{lim,j}$ is the design strain threshold. The indicator does not assert damage from strain alone. It is combined with drift, hysteretic history, inspection evidence, and model confidence. The tendon-force reserve is $r_T = (T_{allow} - |T_c|) / T_{allow}$, and is required to remain non-negative during any proposed action. The uncertainty index can aggregate normalized innovation, missing-channel fraction, timing skew, and disagreement between response-model predictions and measurements. If ξ exceeds a project-defined limit, the controller is inhibited even when the nominal drift estimate appears favorable.

The classifier maps the state estimate into one of four states: S0, normal/operational; S1, inspection required; S2, recoverable damage; and S3, escalation. S0 requires low residual drift, adequate data quality, and no critical component indicator. S1 is selected when the data do not support a defensible automated distinction, when visible damage evidence is incomplete, or when nonstructural hazards are possible. S2 requires that damage be concentrated in designated replaceable components, that the core retain a positive tendon-force reserve, that the required restoration action satisfy bounds, and that a responsible engineer approve the proposed work plan. S3 is selected for any indication of loss of gravity-load path, core instability, tendon-force exceedance, excessive residual drift, actuator saturation, or inconsistent measurements. The classifier is deliberately conservative. It identifies whether the framework may prepare a restoration recommendation; it does not make a legal occupancy decision.

For a single generalized drift coordinate ϕ , the restoring-balance used in the benchmark is written as $M_{req} = \max[0, M_{f,res} + M_P\Delta - M_c - M_a, avail]$, where $M_{f,res}$ is the residual resistance associated with the damaged/restrained fuses, $M_P\Delta$ is the destabilizing gravity-induced moment at the measured residual drift, M_c is the available moment from the self-centering core, and $M_a, avail$ is the verified actuator contribution. In the reported deterministic scenario table, $M_a, avail$ is held at zero so that the effect of fuse release and core capacity is transparent. A non-zero, governed actuator contribution may be introduced only after the state estimator, tendon-force reserve, and travel limits permit it. This form is consistent with the basic physical insight that residual restoring demand depends on the competition between locked damage, P- Δ destabilization, and recoverable restoring capacity, while avoiding a claim that the scalar equation replaces nonlinear frame analysis.

$$M_{req} = \max[0, M_{f,res} + M_P\Delta - M_c - M_a, avail] \quad (3)$$

The cooperative controller selects an action vector $a = [\lambda_f, \Delta_a, F_a, v_a]^T$, where λ_f represents the ordered release or replacement status of designated fuses, Δ_a is allowable actuator travel, F_a is actuator force, and v_a is actuator

velocity. It minimizes $J(a) = w_\phi \phi_{res}(a)^2 + w_F \|F_a\|^2 + w_T P_T(a) + w_R P_R(a) + w_t t(a)$. Here, P_T penalizes depletion of tendon-force reserve, P_R penalizes commands that approach structural or operational limits, and t is the estimated action duration. The weights encode project priorities and must be approved by the design team. The optimization is subject to $|F_a| \leq F_a, max, |\Delta_a| \leq \Delta_a, max, |v_a| \leq v_a, max, r_T \geq r_T, min, \xi \leq \xi, max, d_{f,j} \in D_{release}$, and a human authorization flag $h_{auth} = 1$. The final constraint is essential: no optimization result is executable without the approved decision state and an explicit authorization workflow.

$$\min J(a) = w_\phi \phi_{res}(a)^2 + w_F \|F_a\|^2 + w_T P_T(a) + w_R P_R(a) + w_t t(a) \quad (4)$$

The restoration sequence is staged to avoid using active force to overpower an uncharacterized residual mechanism. Stage A performs data synchronization, sensor health screening, and a state-estimation update. Stage B compares the current digital-twin prediction with the observed response and records uncertainty. Stage C classifies the structure and initiates a field inspection when the decision is S1 or S3. Stage D, available only under S2, removes or releases the specific replaceable components approved in the work plan. Stage E re-estimates the state after the mechanism changes. Stage F applies bounded core-assisted or actuator-assisted restoration in small increments, with a verification measurement after each increment. Stage G creates a repair record containing observations, estimates, commands, overrides, and final inspection findings. Figure 2 depicts this workflow. The approach is compatible with the natural-control and post-earthquake realignment ideas developed for repairable moment-frame/rocking-core systems [32], but it extends them by specifying a monitoring-to-decision and decision-to-command interface.

Analytical study workflow

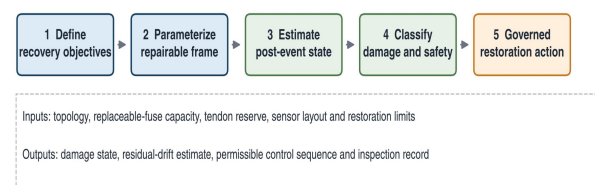


Fig. 2. Analytical study workflow. The sequence begins with recovery objectives and ends with governed action and a verified record.

The sensing strategy is intentionally sparse but redundant at decisive locations. Each storey receives acceleration and relative-displacement channels to estimate drift and identify sensor disagreement. Strain-gauge pairs are placed on protected replaceable-fuse zones so that the measurement is linked to the intended repair mechanism rather than a diffuse, inaccessible damage region. Tendon-force sensors observe the available restoring reserve in the core. Base-shear or foundation-reaction measurements may improve model updating when feasible, but they are not assumed in the analytical benchmark. Time synchronization, calibration records, temperature compensation, anti-alias filtering, data-loss flags, and chain-of-custody controls are part of the measurement system, not post-processing conveniences. The

instrumentation therefore supports both physical diagnosis and the auditability of the subsequent human decision.

A sensitivity and verification plan is built into the method. The analytical model is checked first for sign consistency, boundedness of M_{req} , monotonic response to fuse release, and preservation of non-negative tendon reserve. Subsequently, a nonlinear finite-element model should verify that the chosen generalized coordinate remains representative under higher-mode response, connection slip, geometric nonlinearity, and asymmetric damage. The next validation stage should use component tests to calibrate fuse strain thresholds and release mechanics, followed by real-time hybrid simulation to test end-to-end latency, actuator tracking, power interruption, sensor loss, and communication failure. Finally, a pilot deployment must run in shadow mode: it records recommendations without issuing structural commands until the estimator, workflow, and human factors have been independently verified. These stages reflect the limitations identified in both SHM and active-control literature [7] [19] [24] [25].

IV. ANALYTICAL CASE AND DATA

The numerical material in this paper is a deterministic analytical benchmark, created to expose the proposed variables and decision sequence. It does not use random sampling, field measurements, laboratory repetitions, or a claim of statistically estimated population performance. The two CSV files supplied with the manuscript contain prescribed frame properties and the closed-form scenario values used in Figures 4–6. Their purpose is reproducibility: a reader can recompute the displayed moment balances and inspect the assumptions. The figures should therefore be read as analytical design aids, not as evidence that a particular building will recover within a given time or under a particular earthquake.

The archetype is a regular six-storey steel frame with 3.60 m storey height, two exterior moment-frame lines, a central rocking core, and replaceable beam-end fuses at each level. The six lumped storey masses range from 224 to 247 tonnes; frame lateral stiffness values range from 234 to 276 MN/m; and prescribed fuse-yield moments range from 2.03 to 2.85 MN·m. These values form a transparent parameter set rather than a design for construction. Figure 3 shows the arrangement. The configuration deliberately represents a regular structure so that the relationship between global drift and protected-zone demand remains interpretable. Irregular three-dimensional buildings, discontinuous diaphragms, soft-storey conditions, and soil–structure interaction require a richer model and are outside the benchmark boundary.

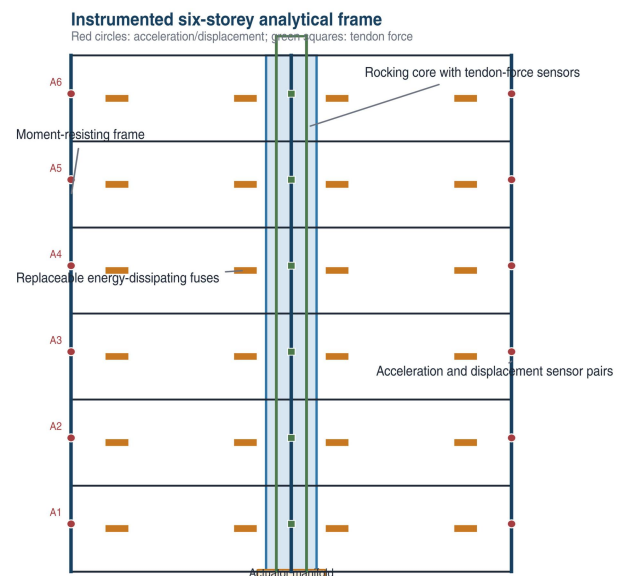


Fig. 3. Instrumented six-storey repairable-frame archetype. Orange elements indicate replaceable fuses; red circles represent acceleration/displacement channels; green squares represent tendon-force channels.

The data channels are organized into a structural-response group and a decision-quality group. Structural-response channels include storey accelerations, relative displacements, fuse strains, and tendon forces. Decision-quality channels include time stamps, missing-data flags, synchronization offsets, range checks, and estimated observation uncertainty. Raw time histories would normally be detrended, synchronized to a common clock, filtered with a cut-off chosen from the structural frequency band and sensor specifications, and transformed into drift, strain, and force features. In the present benchmark, no raw time histories are generated. The preprocessing specification is still included because a real implementation must make each transformation traceable and must avoid treating corrupted, stale, or unsynchronized data as control-quality information (Table II).

TABLE II. MEASUREMENT CHANNELS, QUALITY CONTROLS, AND DECISION ROLES.

Channel	Primary quantity	Quality-control requirement	Decision role
Relative displacement	Interstorey drift and residual deformation	Paired storey; check; per zero range; check; synchronized time stamp	Primary state-estimation input
Accelerometer	Dynamic response and response consistency	Paired storey; bias removal; anti-alias filter; clock-offset check	Rapid-response and model-update input
Fuse strain-gauge pair	Replaceable-fuse demand and release eligibility	Protected zone; calibration; temperature compensation; redundancy check	Mechanism-specific repair input
Tendon-force sensor	Core restoring reserve and force-limit compliance	Protected tendon path; calibration; saturation and drift check	Controller constraint input
Quality-control channel	Timing, loss, communication, and sensor health	Continuous flagging; missingness and innovation thresholds	Control inhibit inspection trigger

Three restoration scenarios are prescribed. The first retains locked replaceable fuses, corresponding to a condition in which the residual mechanism cannot yet be released. The second represents a staged release in which approved fuses are removed or disengaged, thereby reducing the residual fuse moment while maintaining the same core restoring contribution. The third represents a cooperative sequence in which the residual mechanism has been reduced further and the available core restoring moment has increased within its specified reserve. The values are selected to demonstrate the governing equation, not to match a published experimental result. Table III lists the scenario parameters and explicitly distinguishes prescribed inputs from derived analytical outputs.

TABLE III. PRESCRIBED ANALYTICAL BENCHMARK PARAMETERS AND THEIR STATUS.

Parameter	Value	Status / provenance
Storey count	6	Prescribed analytical archetype
Storey height	3.60 m	Prescribed analytical archetype
Lumped storey masses	224–247 tonnes	CSV: analytical_frame_parameter_set.csv
Frame stiffness range	234–276 MN/m	CSV: analytical_frame_parameter_set.csv
Fuse-yield moment range	2.03–2.85 MN·m	CSV: analytical_frame_parameter_set.csv
Locked-fuse residual moment	1.42 MN·m	Prescribed scenario input

Parameter	Value	Status / provenance
Staged-release residual moment	0.64 MN·m	Prescribed scenario input
Cooperative residual moment	0.21 MN·m	Prescribed scenario input
P-Δ moment	0.13 MN·m	Prescribed scenario input
Core restoring moment	0.36 / 0.36 / 0.48 MN·m	Prescribed scenario input

V. RESULTS

The analytical architecture creates a closed information loop rather than a linear monitoring pipeline. As shown in Figure 1, sensor observations enter an acquisition layer that checks synchronization and data quality before the state estimator calculates residual deformation and component demand. The classifier has two distinct branches. An inspection state routes the case to human review; a recoverable-damage state routes an approved case to the cooperative optimizer and then to the command governor. Both inspection outcomes and executed commands return to the digital repair record. This loop matters because a release action alters the structural mechanism: the model must be updated and the state re-estimated before any subsequent restoration increment is proposed.

Figure 2 makes the sequencing constraint explicit. The method does not move directly from a high drift estimate to an actuator command. It first verifies the sensor record, assesses recoverability, identifies the permitted repair action, and imposes travel, force, velocity, and tendon-reserve constraints. The workflow produces two types of output. The first is a structural output, such as an estimated residual drift or a permissible fuse-release set. The second is a decision output, such as an inspection plan, a work order, or an escalation record. This separation prevents a numerical estimate from being misrepresented as a final operational decision.

The prescribed frame topology is shown in Figure 3. Red circular markers indicate paired acceleration and displacement channels at each storey, while green squares represent tendon-force measurements. The protected fuse zones are highlighted as small orange elements at beam ends. The topology reflects a design choice: monitoring is concentrated where the mechanism is intended to be replaceable and where measurements can be interpreted against the global drift state. The central core provides a direct location for sensing the restoring reserve. Table II specifies the measurement roles and quality checks. Because the benchmark includes no empirical noise record, the values in the sensor-observability assessment are normalized design scores rather than estimated detection probabilities.

The recovery-demand envelope in Figure 4 evaluates the prescribed post-event drift state over normalized restoring capacity $M_{0,c}/M_d$ from 0 to 1.20. At each of the three core-to-frame stiffness ratios, residual drift decreases monotonically as the normalized restoring capacity increases. The envelope crosses the illustrative 0.50% drift inspection threshold at approximately $M_{0,c}/M_d = 0.64\text{--}0.70$, depending on the stiffness ratio. The shaded region begins at 0.70 and denotes an analytically low-demand restoration region for this

parameter set. The result should not be interpreted as a universal design threshold. It illustrates that a monitoring-informed controller can use an envelope to distinguish states in which a proposed return action is unlikely to require excessive additional demand from states that require inspection or a different repair strategy.

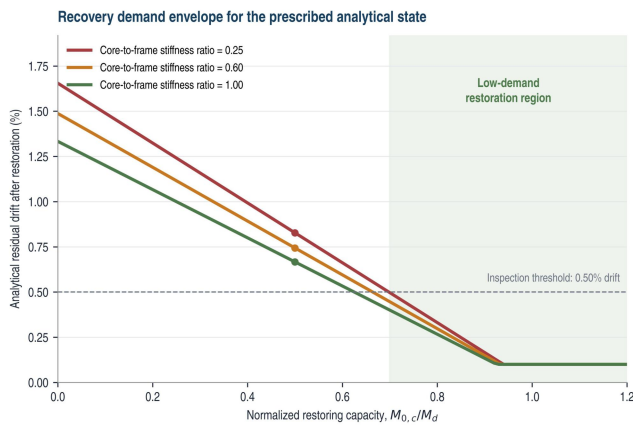


Fig. 4. Recovery-demand envelope for the prescribed analytical state. The plot is a closed-form illustrative calculation, not a field measurement or performance prediction.

The moment balance in Table IV and Figure 5 demonstrates the effect of the staged sequence. With locked fuses, residual fuse resistance is 1.42 MN·m, P-Δ contribution is 0.13 MN·m, and core restoring contribution is 0.36 MN·m. Equation (1) therefore gives a net restoration demand of 1.19 MN·m. After staged release, residual fuse resistance is reduced to 0.64 MN·m; with the same core contribution, the demand is 0.41 MN·m. In the cooperative sequence, residual fuse resistance is 0.21 MN·m and core restoring contribution is 0.48 MN·m. The balance becomes negative before the max operator is applied, yielding $M_{req} = 0.00$ MN·m. This is a deterministic accounting result under the listed assumptions. It demonstrates why removal or release of damage-localized components can be more efficient than attempting to force a restrained damaged frame back to zero drift.

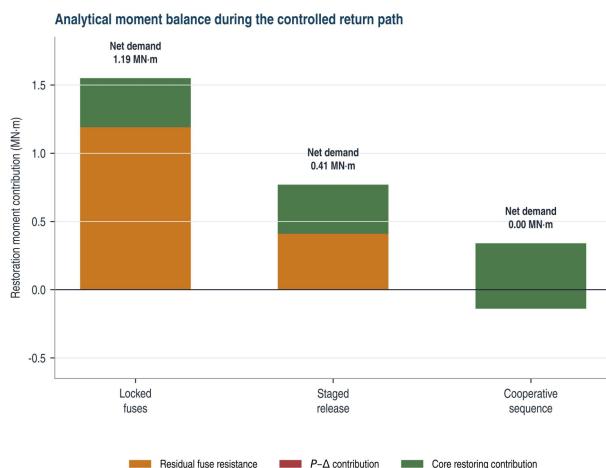


Fig. 5. Analytical restoration moment balance for locked, staged-release, and cooperative sequences. The figure reports prescribed inputs and their closed-form balance only.

TABLE IV. CLOSED-FORM RESTORATION BALANCE FOR THE PRESCRIBED SCENARIOS.

Scenario	$M_{f,rs}$	$M_{P\Delta}$	M_c	M_{req}	Target ϕ_{res} (%)	Interpretation
Locked replaceable fuses	1.42	0.13	0.36	1.19	1.50	Inspection or high-demand restoration case
Staged fuse release	0.64	0.13	0.36	0.41	0.55	Conditional recovery; verify after release
Cooperative release plus core reserve	0.21	0.13	0.48	0.00	0.10	Low-demand return path within the prescribed model

The scenario outputs also show the associated residual-drift targets. The locked-fuse scenario retains a prescribed target of 1.50%, the staged-release scenario 0.55%, and the cooperative sequence 0.10%. The values do not represent measured residual drifts. They are target states used to construct a consistent comparison between the recovery-balance calculation and the classification logic. Their role is to show that a framework should make the selected target, the physical mechanism, and the acceptable uncertainty explicit. In an actual project, target drift would be linked to the intended reparability of structural and nonstructural components, code-based acceptance criteria, and the responsible engineer's recovery objectives.

Figure 6 reports a normalized observability matrix for three prescribed sensor configurations. The minimal eight-channel arrangement scores 0.36–0.68 across the five decision variables, with especially weak observability for core rotation and fuse strain. The protected twenty-channel topology raises the scores to 0.79–0.92, and the redundant twenty-eight-channel topology raises them to 0.88–0.97. These numbers are not classification accuracies or probabilities derived from data. They are a transparent topology score assigned to demonstrate the decision principle that a sensor plan should be evaluated against the state variables required for safe sequencing. The protected configuration is selected as the preferred balance in this benchmark because it observes all components needed for the state estimate without assuming that maximal instrumentation is automatically optimal.

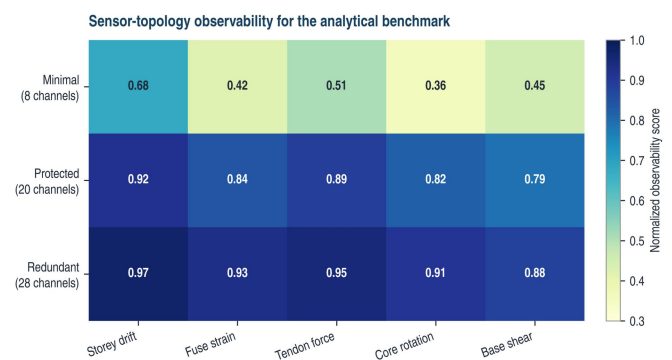


Fig. 6. Normalized observability scores for the prescribed sensor topologies. Scores are design metrics, not empirical classification accuracy.

No p values, confidence intervals, regression coefficients, or statistical significance tests are reported because the benchmark is not an experimental sample or observational

dataset. Instead, verification is performed by deterministic internal checks. First, M_{req} is bounded below by zero. Second, reducing $M_{f, res}$ does not increase M_{req} when other quantities are fixed. Third, increasing M_c does not increase M_{req} when other quantities are fixed. Fourth, each scenario maintains a non-negative tendon-force reserve by construction. Fifth, the controller is disabled whenever the uncertainty threshold or human-authorization condition is violated. Table V records these checks and the corresponding limitation. The absence of empirical statistics is a limitation, not a license to present scenario values as measured performance.

TABLE V. DETERMINISTIC VERIFICATION CHECKS AND STATED BOUNDARIES.

Check	Criterion	Outcome	Boundary
Non-negative restoration demand	$M_{req} = \max(0, \text{balance})$	Pass by equation construction	Does not prove physical feasibility.
Fuse-release monotonicity	Lower residual fuse term cannot increase M_{req} when other terms remain fixed	Pass for prescribed scenarios	Nonlinear interaction requires finite-element verification.
Core-capacity monotonicity	Higher available core moment cannot increase M_{req} when other terms remain fixed	Pass for prescribed scenarios	Actual core response depends on tendon, foundation, and connection condition.
Tendon reserve constraint	$rT \geq rT_{min}$ for every command	Specified as a hard controller constraint	No dynamic tendon model is calibrated here.
Data-quality inhibit	$\xi \leq \xi_{max}$ and human authorization required	Specified as a hard workflow constraint	Thresholds require project-specific validation.

VI. DISCUSSION

The framework contributes an operational bridge between three research domains that are often considered separately. SHM provides information about structural condition, repairable systems shape where damage may occur, and active or semi-active devices provide the possibility of bounded intervention. The bridge is the decision architecture: the same digital record that stores measurements also stores classification, constraints, human review, proposed actions, executed commands, and verification observations. This architecture matters for scientific reproducibility and for governance. A future real-time system can only be audited if it is possible to identify which observations, model parameters, and authorization state led to a particular recommendation or command.

The results reinforce a physical distinction between restoring a frame and forcing a damaged frame to appear undeformed. When residual demand resides in replaceable elements, staged release can reduce the resisting mechanism before a return action is attempted. The analytical balance shows this effect directly: reducing the residual fuse term decreases the net restoration demand without requiring a larger external actuator force. This is consistent with the recovery-oriented logic of self-centering and replaceable-fuse systems, which seek to control the location and consequence of inelastic action [11]–[17] [30]. It also aligns with earlier

work on sustainable seismic design and post-earthquake realignment, which emphasizes purpose-specific detailing, controlled mechanisms, restoring force, and monitored repair operations [32]. The present paper differs in its emphasis on a formal human-supervised data and command workflow.

The role of the rocking core is also clarified. In the benchmark it is not treated as a generic stiffening element. It is a monitored source of recoverable restoring capacity whose tendon-force reserve constrains the controller. This distinction is important because a core that has exceeded allowable tendon force, suffered connection damage, or displays inconsistent sensor readings cannot be safely represented as an available restoring source. The state estimator and classifier must expose that uncertainty. Thus, the framework prevents a common conceptual error: using a nominal design stiffness or preload as if it were a verified post-event property. Real systems must update the estimate from measured force, deformation, and inspection evidence.

The monitoring strategy follows from the intended structural mechanism. Sparse acceleration monitoring can be useful for rapid drift estimation [9], but it does not directly identify the condition of a replaceable fuse or the reserve in a restoring tendon. Conversely, a strain gauge on a fuse does not provide a complete picture of global drift, torsion, or nonstructural demand. The protected topology in Figure 6 illustrates the value of complementary channels. It also supports graceful degradation: if one acceleration channel is lost, relative displacement and strain data may still bound the state; if tendon sensing is lost, the system should fail closed to inspection rather than infer reserve from a stale model. This approach is consistent with the sensor-placement and digital-twin literature, which regards measurement value, uncertainty, and model update as linked design variables [10] [28] [29].

Active cooperative control after an earthquake should be judged by a more demanding standard than ordinary feedback regulation. The action is applied to a potentially damaged structure, the consequence of a wrong command may be serious, and the desired output includes documentation and repair coordination. The command governor therefore serves as a safety envelope. It must impose force, travel, velocity, power, and tendon-reserve limits; detect stale or inconsistent data; and stop automatically under saturation or communication loss. Semi-active devices can offer a useful passive fallback [21], but passive fallback alone does not establish a fault-tolerant restoration protocol. A complete implementation must test sensor dropout, clock errors, actuator lag, electrical failure, cyber compromise, and changes in structural stiffness. Real-time hybrid simulation is a particularly appropriate intermediate test environment because it exposes these interfaces before building deployment [24] [25].

Several limitations define the boundary of the present work. The frame is regular and represented by a reduced generalized coordinate, whereas actual buildings can exhibit higher-mode effects, torsion, diaphragm flexibility, foundation compliance, and localized connection behavior. The model does not simulate ground-motion ensembles, cumulative aftershocks, damage progression, nonstructural components, utilities, occupant behavior, repair procurement, or workforce availability. The observability scores are prescribed topology metrics, not estimates from a validated classifier. The scenario values are closed-form analytical values, not laboratory or field measurements. Finally, neither

the SHM state nor the controller output is a legal determination of safety, reoccupation, or repair adequacy. Those decisions require competent engineering assessment and the relevant authority processes [4] [2] [6].

These limitations motivate a staged research agenda. First, component tests should establish fuse strain thresholds, release mechanics, residual-friction behavior, and inspection protocols. Second, a nonlinear three-dimensional digital twin should be calibrated against cyclic and shake-table data, including bias from nonstructural restraint and geometric nonlinearity. Third, a real-time hybrid experiment should connect a numerical multi-storey frame to physical actuators and replaceable components while imposing measured latency, noise, dropout, and power-failure scenarios. Fourth, human factors research should examine whether engineers and inspectors can interpret the uncertainty displays, work orders, and stop conditions rapidly and consistently. Finally, a monitored pilot system should operate in shadow mode before it is permitted to influence a post-event restoration action. This sequence preserves the methodological promise of cooperation without overstating current readiness.

VII. CONCLUSIONS

This paper presented an original framework for structural health monitoring and active cooperative control of repairable frame structures during rapid post-earthquake restoration. The framework treats recovery as a controlled, human-supervised decision process rather than a simple extension of earthquake response control. Heterogeneous measurements update a digital-twin state estimate; the estimate is qualified by data quality and uncertainty; a conservative classifier separates inspection, recoverable-damage, and escalation states; and a command governor constrains any approved restoration action. The architecture preserves a traceable link from sensor observation to repair record.

The deterministic six-storey benchmark clarified the proposed mechanics. Under the prescribed values, the net restoration demand was 1.19 MN·m with locked fuses, 0.41 MN·m after staged fuse release, and 0.00 MN·m after the specified cooperative sequence increased available core restoring capacity. These values are analytical demonstrations, not empirical performance claims. Their purpose is to show that physical reparability, monitoring information, and action sequencing must be designed together. A controller should not attempt to overpower a locked residual mechanism when a verified release or replacement operation can reduce the demand more safely and transparently.

The practical implication is that resilient frames should be detailed not only for seismic strength and ductility but also for observability, access, replaceability, and controlled return. Protected sensing zones, monitored restoring reserves, reversible work steps, and auditable digital records are as important to the framework as the control law itself. Future work must validate the method through component tests, nonlinear simulation, real-time hybrid experiments, and human-supervised field trials. Until those stages are completed, the framework should be used as a research and design-planning tool rather than as an autonomous safety or reoccupation system.

A. Data Availability and Implementation Boundary

The editable CSV files “analytical_frame_parameter_set.csv” and “analytical_restoration_scenarios.csv” contain the p

rescribed inputs and closed-form scenario values used in the figures. They are supplied to enable recalculation of the analytical displays. They are not field measurements, test data, or a validated control dataset. The accompanying figure inventory identifies the provenance of each visual. A project-specific implementation would require an approved structural model, calibrated sensors, tested devices, cybersecurity and power-failure procedures, a responsible engineer, and the relevant authority process.

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