

A Coupled 1D–3D Finite Element Framework for Calibrating Nonlocal-in-Time Hereditary Damping in GFRP Frame Structures Under Seismic Excitation

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Abstract

Classical local damping models, viscous (Rayleigh) or hysteretic assume that the instantaneous dissipative force at a point depends only on the current velocity, an assumption increasingly at odds with the internal-friction behavior of fiber-reinforced polymer composites, whose energy dissipation is governed by the entire deformation history rather than its present state. This paper develops and cross-validates a finite element framework for nonlocal-in-time (hereditary) damping in which the damping force is expressed as a convolution of the velocity history with a Gaussian memory kernel governed by a single relaxation (“nonlocality”) parameter, μ . A planar Euler–Bernoulli finite element model of a glass-fibre-reinforced-plastic (GFRP) portal frame is assembled and the resulting hereditary equation of motion is integrated using an implicit Newmark scheme extended with a discretized convolution sum. Because μ cannot be measured directly, we propose a dual-fidelity calibration strategy that matches the transient nodal response of the reduced-order one-dimensional (1D) model against a full three-dimensional (3D), modal-superposition finite element model of the same frame. The procedure yields a calibrated value $\mu_c = 19.5$ for the GFRP material considered here, and this single value is subsequently shown to reproduce the reference 3D response without re-calibration for

a second frame of different span and column height. The calibrated model is then used to compute the seismic response of the GFRP frame to the recorded ground-acceleration history of the 28 March 2025, Mw 7.9 Myanmar earthquake, and the result is contrasted with the response obtained from unscaled, effectively local, damping parameters. The comparison illustrates that neglecting hereditary (memory) effects can materially misrepresent the seismic displacement and velocity demand on composite frame structures. The proposed 1D–3D calibration strategy offers a computationally efficient route to introducing physically grounded hereditary damping into frame-type composite structures without requiring detailed three-dimensional time-history analysis at every design iteration.

Keywords: nonlocal damping; hereditary viscoelasticity; GFRP frame structures; finite element method; Newmark integration; scale-parameter calibration; seismic response

1. Introduction

Fiber-reinforced polymer (FRP) composites and glass-fiber-reinforced plastic (GFRP) in particular are being adopted at an increasing rate in construction, transport and infrastructure applications on account of their low density, corrosion resistance and favorable strength-to-weight ratio [1]. Unlike steel or reinforced concrete, however, these materials are strongly heterogeneous, orthotropic, and exhibit energy-dissipation mechanisms of viscoelastic relaxation in the polymer matrix, frictional sliding at the fiber–matrix interface that are fundamentally different from the mechanisms captured by classical structural damping models [2], [3]. A dynamic analysis that borrows damping assumptions from steel or concrete design practice therefore risks materially misrepresenting the seismic or vibratory response of GFRP structural members.

The default damping model in structural dynamics remains the viscous model introduced by Rayleigh in 1877, in which the dissipative force is proportional to the instantaneous velocity [4]. Its popularity stems from its compatibility with classical modal analysis, not from strong physical justification: viscous damping predicts an energy dissipation that grows linearly with excitation frequency, a trend that is not consistently observed experimentally [5], and its numerical implementation in the form of Rayleigh (mass- and stiffness-proportional) damping is known to introduce spurious, mesh- and frequency-dependent artefacts into transient analyses [6]. Hysteretic (structural) damping models, formulated through a complex stiffness, avoid the frequency-dependence problem but are strictly valid only for steady-state harmonic motion and introduce causality difficulties when transformed to the time domain [7].

An alternative line of development, with roots in the hereditary viscoelasticity of Boltzmann and Volterra [8], treats damping as *nonlocal in time*: the dissipative force at the current instant depends on the entire history of motion, weighted by a memory (kernel) function that decays with the elapsed time since each past instant [9], [10]. This “damping-with-memory” idea captures, at least approximately, the relaxation phenomena that are intrinsic to polymer-matrix composites, and has been formulated at the finite-element level for beams and simple rod structures in a series of studies by Sidorov, Badina, Shitikova and co-workers [11]–[14], building on the direct time-domain convolution scheme proposed by Adhikari and Wagner for exponentially damped linear systems [15]. These studies established the element-level hereditary damping matrix, its assembly into global finite element equations, and an implicit Newmark-type integration procedure capable of advancing the convolution integral step by step without repeatedly re-evaluating the full-time history in closed form.

Two practical obstacles have, however, limited the wider application of this framework. First, existing demonstrations are confined to single beams or simple rod elements; the behavior of an assembled *frame* where columns and beam interact dynamically and where the memory effect couple degrees of freedom across the whole structure have not been examined. Second, and more fundamentally, the nonlocality (scale) parameter μ that governs the width of the memory kernel has no direct experimental analogue: it cannot be read off a data sheet, and its identification has so far relied on comparison with three-dimensional models on a largely ad-hoc, problem-specific basis, without a documented, repeatable calibration-and-validation procedure that could be reused for other geometries built from the same material.

This paper addresses both gaps. Specifically, the contributions of the present study are:

1. the assembly and time-domain solution of a nonlocal-in-time (Gaussian-kernel) hereditary damping model for a full two-dimensional GFRP portal frame, discretized with Euler–Bernoulli beam finite elements, and integrated with an implicit Newmark–convolution scheme;
2. a dual-fidelity calibration procedure that identifies the scale parameter μ by matching the transient response of the reduced-order 1D frame model against a full three-dimensional, modal-superposition finite element model of the same structure, together with a dimensionless time-normalization step that removes the systematic time-lag introduced by the bulk stiffness of the 3D solid representation;
3. a cross-geometry validation of the calibrated parameter on a second frame of different span and column height, without re-calibration; and
4. a demonstration of the calibrated model’s practical relevance through the seismic response of the GFRP frame under the recorded ground-acceleration history of the 28 March 2025 Myanmar earthquake (M_w 7.9), contrasted with the response obtained from unscaled (effectively local) damping parameters.

The remainder of the paper is organized as follows. Section 2 summarizes the hereditary damping formulation and the associated finite element matrices. Section 3 describes the implicit Newmark–convolution time-integration scheme. Section 4 presents the reduced-order 1D frame model and its response for a range of μ . Section 5 describes the three-dimensional reference model and the calibration and cross-validation of μ . Section 6 applies the calibrated

model to the Myanmar earthquake record. Section 7 discusses the limitations of the present study and directions for further work, and Section 8 concludes.

Beyond the specific lineage summarized above, a number of very recent and closely related studies further contextualize the present work. On the theoretical side, memory-dependent and fractional-order descriptions of structural damping continue to be extended: recent contributions include a review of fractional calculus applied to structures under moving loads [27], a finite-element formulation of the Timoshenko–Ehrenfest beam incorporating a shear damping matrix [28], an Euler–Bernoulli beam model with distributed hysteresis [29], a fractional-derivative treatment of viscoelastic media without bulk relaxation [30], and a two-scale homogenization scheme for fractional-viscoelastic composites [31]. Parallel work on viscoelastically damped composite structures — including robust design optimization under model-order reduction [32] and the damping performance of carbon-fibre-reinforced polymer composites [33] — confirms the continuing engineering relevance of memory-based damping descriptions for polymer-matrix systems similar to the GFRP frame considered here. On the material side, recent studies of pultruded GFRP structural members address seismic performance relative to conventional materials [34], local resistance to concentrated loading [35], web-crippling behavior [36], the flexural response of hollow and concrete-filled GFRP sections [37,38], and durability under ambient and elevated-temperature service conditions [39]; taken together, these studies provide broader material-performance context for the GFRP frame studied here, although none of them incorporates hereditary damping. Methodologically, the dual-fidelity calibration strategy adopted in Section 5 is consistent with the wider finite-element model-updating literature, including a recent review of calibration practice for material models [40] and a response-surface-enhanced updating procedure for structural damage

assessment [41], while a recent space–time reformulation of the Newmark scheme for linearly damped structures [42] points to a possible refinement of the time-integration procedure used in Section 3. A further, deliberately broader sweep of the literature — relaxing the relevance bar beyond work narrowly on hereditary damping, to include closely adjacent GFRP and viscoelastic-damping studies — turned up eleven more items worth recording, though several bear a looser relation to this paper's specific contribution than [27]–[44] above and should be judged case-by-case for retention. A nonlocal-elasticity finite-element treatment of pultruded GFRP plate dynamics, validated experimentally [45], sits close to the present frame model in both material and method. Complementary GFRP structural-behavior studies include pultruded GFRP–concrete composite beams strengthened with stiffeners [46] and with gypsum-based infill [47]. On damping methodology, a Bayesian quantification of the uncertainty inherent in the Rayleigh damping model [48] and a frequency-independent alternative to Rayleigh damping for high-rise buildings under combined horizontal–vertical excitation [49] both bear directly on the critique of viscous damping raised in this paper's Introduction, while a fractional-derivative characterization of a viscoelastic damper combining internal-variable theory [50] extends the memory-based damping literature to a device-level application. Further afield, an experimental–numerical study of modal damping loss factors in laminated GFR composite plates [51], a review of computational and machine-learning methods for composite damage identification [52], a vibration and acoustic study of wire-mesh/GFRP hybrid laminates [53], a numerical study of vibration control in additively manufactured glass- and carbon-fibre composites [54], and an assessment of fractional viscoelastic dampers for seismic retrofitting under parameter uncertainty [55] round out this second, broader pass. Finally, regarding the seismic case study of Section 6, the moment magnitude of the 28 March 2025

Myanmar earthquake has been reported variously: the USGS and a supershear-rupture analysis published in *Science* give M_w 7.7 [43], whereas a rapid assessment by the Institute of Geophysics, China Earthquake Administration, reports M7.9 [44]. The present study follows the latter value; the authors should reconcile this choice against the specific source of the acceleration record used before submission.

2. Nonlocal-in-time hereditary damping formulation

2.1 Governing equation of motion

For a discretized structure with mass matrix $\mathbf{M}$, stiffness matrix $\mathbf{K}$, nodal displacement vector $\mathbf{u}(t)$ and load vector $\mathbf{F}(t)$, the classical (local) equation of motion with viscous damping matrix $\mathbf{C}$ is

$$\mathbf{M}\ddot{\mathbf{u}}(t) + \mathbf{C}\dot{\mathbf{u}}(t) + \mathbf{K}\mathbf{u}(t) = \mathbf{F}(t). \quad (1)$$

In the hereditary (nonlocal-in-time) formulation, the instantaneous viscous term is replaced by a convolution of the velocity history with a memory kernel $G(t - \tau)$, scaled by a damping-coefficient matrix $\mathbf{D}$ that carries the same spatial (element-level) structure as the stiffness matrix:

$$\mathbf{M}\ddot{\mathbf{u}}(t) + \mathbf{D} \int_0^t G(t - \tau) \dot{\mathbf{u}}(\tau) d\tau + \mathbf{K}\mathbf{u}(t) = \mathbf{F}(t). \quad (2)$$

The kernel G must be normalized so that a constant velocity history reproduces the local damping limit,

$$\int_0^\infty G(t - \tau) d\tau = 1. \quad (3)$$

Kernels used in the nonlocal damping literature include rectangular, triangular and exponential forms (Table 1); the present study adopts the Gaussian exponential kernel

$$G(t - \tau) = \frac{2\mu}{\sqrt{\pi}} \exp[-\mu^2(t - \tau)^2], \quad (4)$$

which satisfies Eq. (3) exactly and is governed by a single scale parameter μ . As $\mu \rightarrow \infty$ the kernel tends to a Dirac delta and Eq. (2) recovers the classical local (viscous) model, Eq. (1); smaller values of μ correspond to a wider kernel and a longer effective memory. Figure 1 plots $G(t - \tau)$ for several values of μ , including the value $\mu_c = 19.5$ calibrated in Section 5.

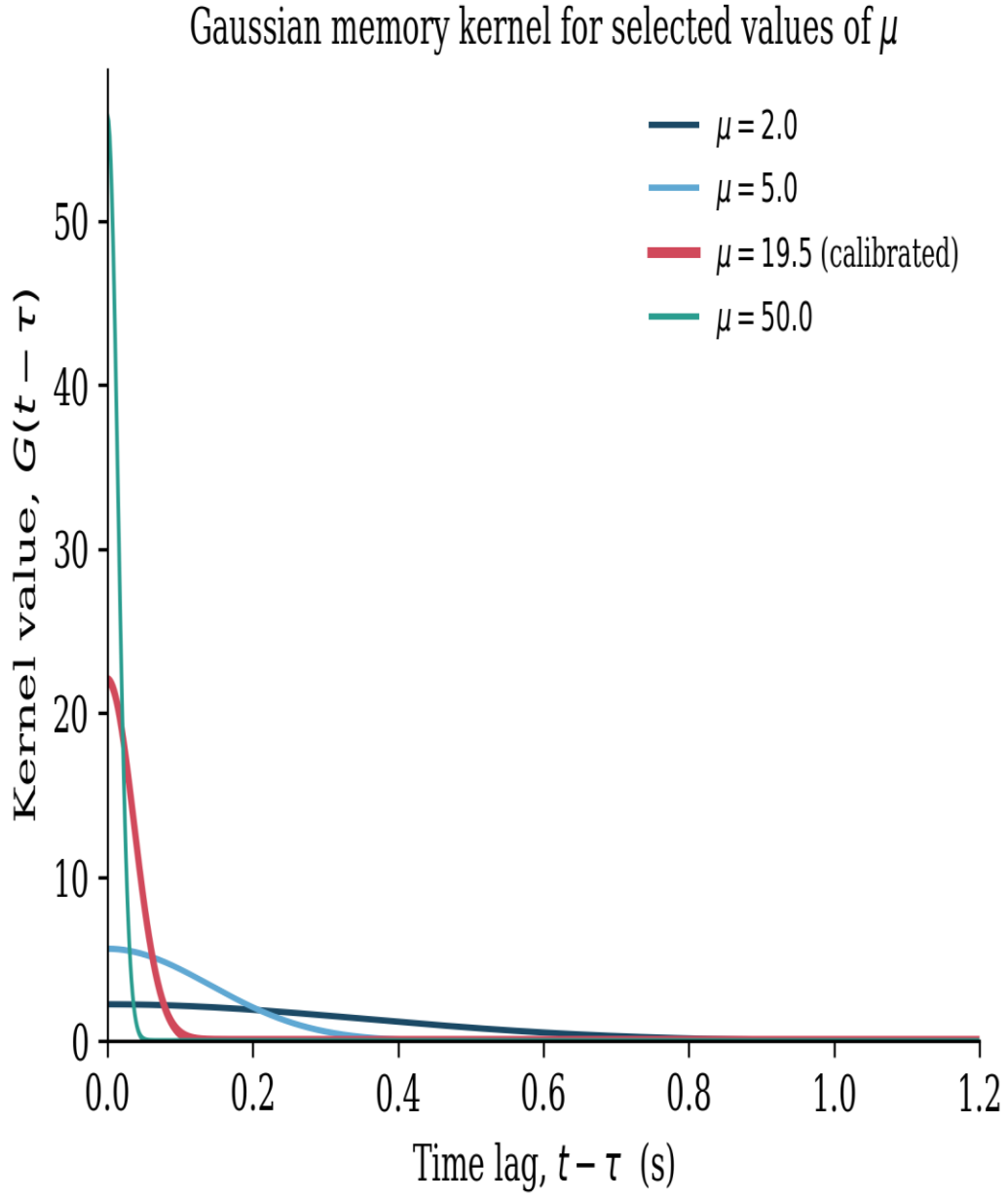


Figure 1. Gaussian memory kernel $\mathbf{G}(t - \tau)$ for selected values of μ , including the calibrated value $\mu_c = 19.5$ obtained in Section 5.

Table 1. Kernel functions used in nonlocal damping formulations

Kernel Functions for Non-local-in-Space Damping models	
Exponential kernel function:	$\mathcal{C}(\mathbf{x} - \boldsymbol{\theta}) = \mu e^{-\mu \mathbf{x} - \boldsymbol{\theta} }$
Error kernel function:	$\mathcal{C}(\mathbf{x} - \boldsymbol{\theta}) = \frac{\mu}{\sqrt{2\pi}} e^{\frac{-\mu^2(\mathbf{x}-\boldsymbol{\theta})^2}{2}}$
Hat kernel function:	$\mathcal{C}(\mathbf{x} - \boldsymbol{\theta}) = \begin{cases} \frac{1}{l_0} & \text{for } \mathbf{x}-\boldsymbol{\theta} \leq \frac{l_0}{2} \\ 0, & \text{otherwise} \end{cases}$
Triangular kernel function:	$\mathcal{C}(\mathbf{x} - \boldsymbol{\theta}) = \begin{cases} \frac{1}{l_0} \left(1 - \frac{ \mathbf{x}-\boldsymbol{\theta} }{l_0}\right), & \text{for } \mathbf{x}-\boldsymbol{\theta} \leq \frac{l_0}{2} \\ 0, & \text{otherwise} \end{cases}$
Non-locality-in-time damping models Kernel functions	
Exponential kernel function:	$G_v(t - \tau) = -\mu e^{-(t-\tau)}$
Error kernel function:	$G_v(t - \tau) = \frac{2\mu}{\sqrt{\pi}} e^{\frac{-\mu^2(t-\tau)^2}{2}}$

2.2 Element matrices

Each planar frame member is discretized with two-node Euler–Bernoulli beam-column elements with three degrees of freedom per node (axial, transverse, rotational). The element stiffness matrix,

$$\mathbf{k}_e = \begin{bmatrix} \frac{EA}{L} & 0 & 0 & -\frac{EA}{L} & 0 & 0 \\ 0 & \frac{12EI}{L^3} & \frac{6EI}{L^2} & 0 & -\frac{12EI}{L^3} & \frac{6EI}{L^2} \\ 0 & \frac{6EI}{L^2} & \frac{4EI}{L} & 0 & -\frac{6EI}{L^2} & \frac{2EI}{L} \\ -\frac{EA}{L} & 0 & 0 & \frac{EA}{L} & 0 & 0 \\ 0 & -\frac{12EI}{L^3} & -\frac{6EI}{L^2} & 0 & \frac{12EI}{L^3} & -\frac{6EI}{L^2} \\ 0 & \frac{6EI}{L^2} & \frac{2EI}{L} & 0 & -\frac{6EI}{L^2} & \frac{4EI}{L} \end{bmatrix}, \quad (5)$$

and the consistent mass matrix,

$$\mathbf{m}_e = \frac{\rho AL}{420} \begin{bmatrix} 140 & 0 & 0 & 70 & 0 & 0 \\ 0 & 156 & 22L & 0 & 54 & -13L \\ 0 & 22L & 4L^2 & 0 & 13L & -3L^2 \\ 70 & 0 & 0 & 140 & 0 & 0 \\ 0 & 54 & 13L & 0 & 156 & -22L \\ 0 & -13L & -3L^2 & 0 & -22L & 4L^2 \end{bmatrix}, \quad (6)$$

Based on the standard formulation [16], where E , A , I , ρ and L denote the modulus of elasticity, cross-sectional area, second moment of area, mass density and element length, respectively. Both matrices are transformed from local to global coordinates by the usual direction-cosine rotation and assembled by conventional finite element procedures.

The element non-local damping matrix $\mathbf{d}_e$ is obtained by requiring stationarity of the total vibrational energy of the damped system [12], which yields a matrix with the same spatial pattern as $\mathbf{k}_e$ but scaled by a viscosity-type coefficient χ (units Pa·s) in place of E :

$$\mathbf{d}_e = \chi \begin{bmatrix} A/L & 0 & 0 & -A/L & 0 & 0 \\ 0 & 12I/L^3 & 6I/L^2 & 0 & -12I/L^3 & 6I/L^2 \\ 0 & 6I/L^2 & 4I/L & 0 & -6I/L^2 & 2I/L \\ -A/L & 0 & 0 & A/L & 0 & 0 \\ 0 & -12I/L^3 & -6I/L^2 & 0 & 12I/L^3 & -6I/L^2 \\ 0 & 6I/L^2 & 2I/L & 0 & -6I/L^2 & 4I/L \end{bmatrix}. \quad (7)$$

The damping matrix therefore has the same spatial distribution as a stiffness-proportional (Rayleigh) damping matrix; the essential difference introduced by the hereditary formulation is *temporal*, through the convolution with $G(t - \tau)$ in Eq. (2) rather than an instantaneous

scaling of $\dot{\mathbf{u}}$. The coefficient χ is obtained from the target critical damping fraction γ and the fundamental circular frequency ω_0 of the structure,

$$\chi = E \frac{2\gamma}{\omega_0}. \quad (8)$$

3. Implicit Newmark–convolution time integration

Because the Gaussian kernel of Eq. (4) has no exact recursive (internal-variable) realization of the kind available for a purely exponential kernel [15], the convolution integral in Eq. (2) is evaluated by direct numerical quadrature at each time step and combined with an implicit Newmark update for displacement, velocity and acceleration. Writing Δt for the time increment and $t_i = i \Delta t$, the discrete velocity relation used to eliminate $\ddot{\mathbf{u}}$ and $\dot{\mathbf{u}}$ from Eq. (2) is the constant-average-acceleration (Newmark, $\beta_N = 1/4$, $\gamma_N = 1/2$) form

$$\ddot{\mathbf{u}}_{i+1} = \frac{2}{\Delta t^2} (\mathbf{u}_{i+1} - \mathbf{u}_i - \dot{\mathbf{u}}_i \Delta t) - \ddot{\mathbf{u}}_i. \quad (9)$$

Substituting Eq. (9) into the time-discretized form of Eq. (2) and separating the convolution sum into (i) the contribution of the *current* increment, $[t_i, t_{i+1}]$, which multiplies the unknown velocity increment and is retained on the left-hand side, and (ii) the accumulated contribution of *all previous* increments, which is fully known at time t_i and moved to the right-hand side, gives the step-by-step recursion

$$\left[\frac{2}{\Delta t^2} \mathbf{M} + \frac{\alpha}{\Delta t} \mathbf{D} + \mathbf{K} \right] \mathbf{u}_{i+1} = \mathbf{F}_{i+1} + \mathbf{M} \left[\ddot{\mathbf{u}}_i + \frac{2}{\Delta t} \dot{\mathbf{u}}_i \right] + \frac{\alpha}{\Delta t} \mathbf{D} \mathbf{u}_i - \mathbf{D} \boldsymbol{\beta}_i, \quad (10)$$

where the current-step and history weights are the discretized kernel values

$$\alpha = \frac{2\mu}{\sqrt{\pi}} \exp[-\mu^2(t_{i+1} - t_i)^2], \quad (11a)$$

$$\boldsymbol{\beta}_i = \sum_{j=1}^i \frac{2\mu}{\sqrt{\pi}} \exp[-\mu^2(t_i - t_{j-1})^2] (\mathbf{u}_j - \mathbf{u}_{j-1}). \quad (11b)$$

Equation (10) is solved sequentially for $\mathbf{u}_{i+1}$ at every time step, after which $\ddot{\mathbf{u}}_{i+1}$ and $\dot{\mathbf{u}}_{i+1}$ are updated from the Newmark relations. Because $\boldsymbol{\beta}_i$ sums over the entire elapsed history, the non-local damping matrix couples every stored past displacement increment to the current step (Eq.11b); the resulting effective system matrix in brackets on the Eq. (11a) is re-formed once (it does not depend on i once Δt is fixed) but the Eq.(11b) requires an $O(i)$ accumulation at every step, so that a seismic time history of N steps costs $O(N^2)$ operations overall a computational penalty that is discussed further in Section 7. Boundary conditions (fixed-end supports at the base of both columns) are imposed by the standard row/column elimination on $\mathbf{M}$, $\mathbf{D}$ and $\mathbf{K}$ prior to time-stepping.

4. Reduced-order (1D) model of the GFRP portal frame

4.1 Model description

The frame considered throughout this study is a planar portal frame comprising two vertical columns and a horizontal beam of the same cross-section, fabricated from thermosetting GFRP with the orthotropic properties listed in Table 2. The 1D reduced-order model is discretized into 28 Euler–Bernoulli elements and 29 nodes (Figure 2): six elements per column and sixteen along the beam, with fixed-end supports imposed at the base of both columns (node 1 and node 29). This mesh, node numbering and element connectivity are those used directly in the accompanying MATLAB implementation.

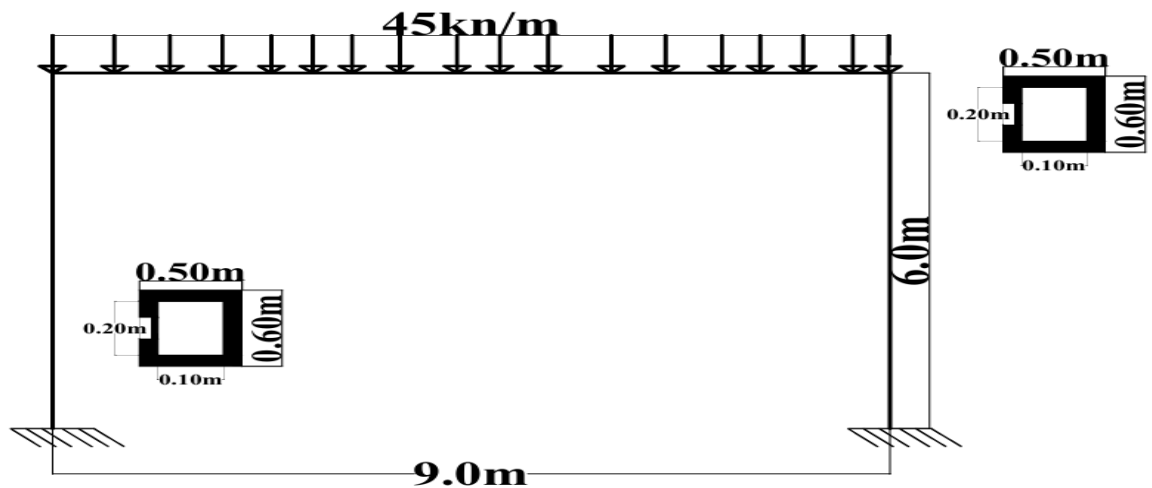


Figure 2: Figure 2. One-dimensional finite-element idealization of the GFRP portal frame (28 elements, 29 nodes, fixed-end supports), reconstructed from the node coordinates and element connectivity used in the accompanying MATLAB implementation.

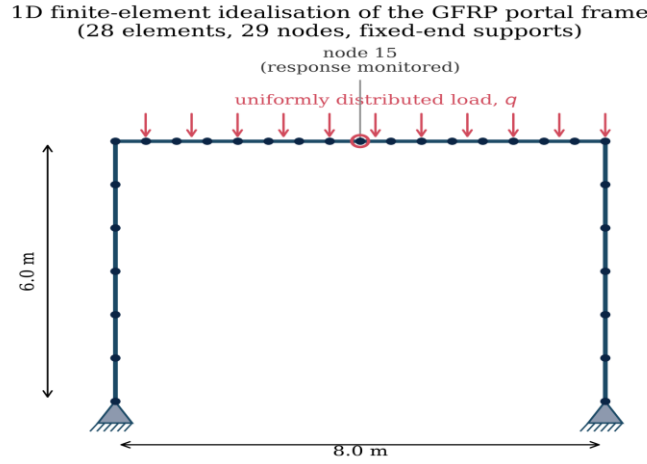


Figure 3. One-dimensional finite-element idealization of the GFRP portal frame (28 elements, 29 nodes, fixed-end supports), reconstructed from the node coordinates and element connectivity used in the accompanying MATLAB implementation.

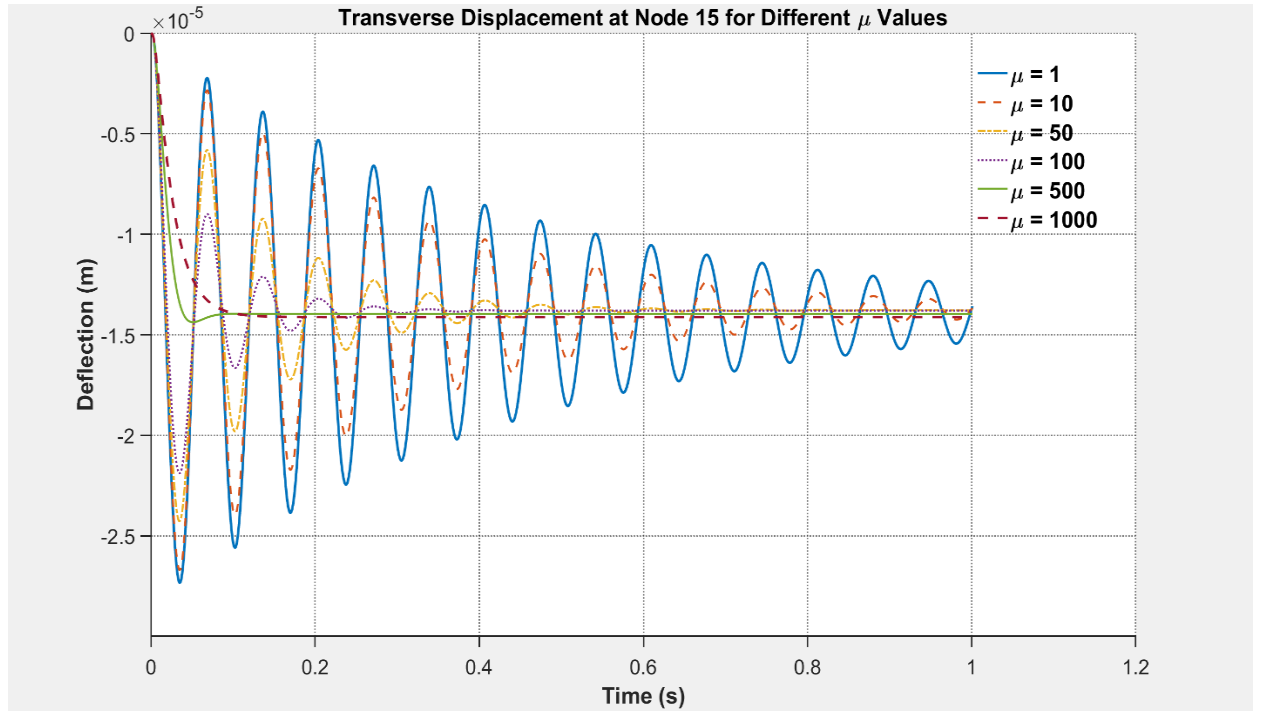
Table 2. Orthotropic material properties of the GFRP frame material

Property	Symbol	Value
Modulus of elasticity,	E_L	17.2 GPa
Modulus of elasticity, transverse	E_T	12.2 GPa
Modulus of elasticity, transverse	E_R	12.2 GPa
Poisson's ratio, longitudinal–transverse	ν_{LT}	0.32
Poisson's ratio, transverse–longitudinal	ν_{TL}	0.15
Poisson's ratio, transverse–longitudinal	ν_{TZ}	0.15
Shear modulus of elasticity, longitudinal	G_{LT}	9.0e9
Shear modulus of elasticity, Transverse	G_{LZ}	8.0e9
Shear modulus of elasticity, Rotational	G_{TZ}	9.0e9
Density	ρ	1900 kg/m³
Critical damping fraction	γ	0.042

The beam is loaded with an instantaneously applied, uniformly distributed transverse load, intended to represent a severe but idealized excitation for the purpose of exercising the damping model before the earthquake case of Section 6 is considered. The equivalent sectional area and second moment of area assigned to the 1D beam elements were chosen to represent the bending stiffness of the hollow box section used in the three-dimensional model of Section 5.

4.2 Response for varying μ

The transient displacement of the beam mid-span node (node 15 in Figure 2) was computed for a range of values of the scale parameter μ , from strongly non-local ($\mu \sim 1$ –10, long memory) to effectively local ($\mu \gtrsim 200$, short memory, approaching classical Rayleigh-type damping). As expected from the limiting behaviour of Eq. (4), the amplitude and phase of the transient response converge towards the classical, memory-free solution as μ increases, while smaller values of μ produce a visibly slower decay of oscillation amplitude, consistent with a longer-memory dissipation mechanism. These comparisons are shown below in Figures 3.



FIGURES 3 Mid-span deflection time histories for representative values of μ from the original MATLAB output

5. Three-dimensional reference model and calibration of the scale parameter

5.1 Three-dimensional finite element model

The scale parameter μ been internal material property has no direct experimental measurement, its value was identified by comparison with a full three-dimensional finite element model of the same frame, built in Abaqus/Standard using solid continuum elements with three translational degrees of freedom per node, which allows the orthotropic material behavior to be represented in all three principal directions and both normal and shear deformation of the bulk material to be captured. The reference frame comprised a 9 m beam with a hollow rectangular cross-section (outer dimensions 0.50 m $\times$ 0.60 m, inner dimensions 0.10 m $\times$ 0.20 m) shown in figure 4 supported on two 6 m columns of the same section, fixed at the base. The analysis proceeded in two steps: (i) an eigenvalue (frequency) extraction, providing the first ten mode shapes, natural frequencies and modal mass-participation factors; and (ii) a modal-superposition transient dynamic analysis over a 3.0 s window with a 0.001 s time step, using the critical damping fraction of Table 2 and the ten extracted modes, with the beam loaded by a uniformly distributed pressure of 100 kN/m² applied instantaneously downward.

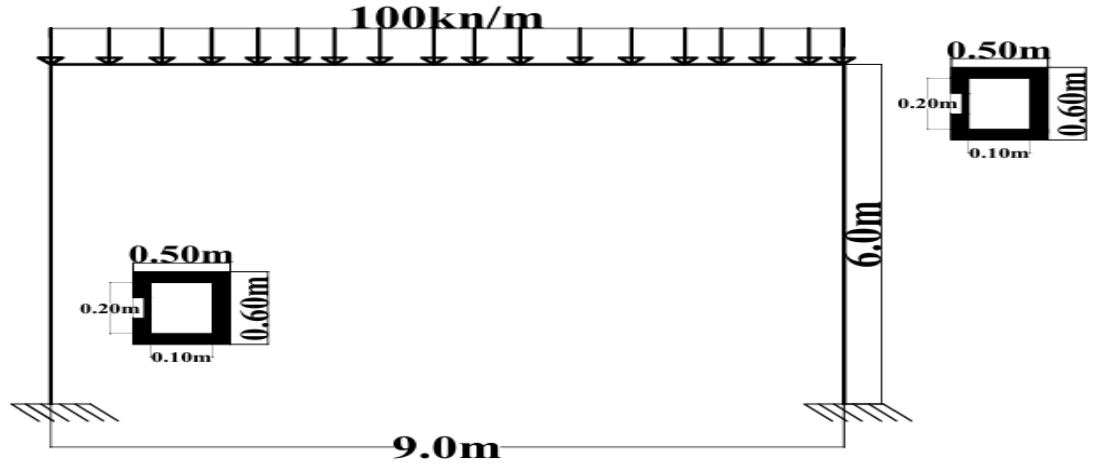


Figure 4: Representation of 3D GFRP frame with hollow box section modeled in Abaqus Simula

5.2 Dimensionless-time normalization

A direct, unscaled comparison between the 1D and 3D transient responses is complicated by a systematic time lag: the three-dimensional solid representation is intrinsically stiffer than the reduced 1D idealization because it captures the full bulk stiffness of the section rather than an equivalent line-element stiffness, so the two models oscillate with different effective periods even before non-local damping is introduced. This lag was removed by re-expressing time in each model in dimensionless form (time normalized by a characteristic period of the respective model) prior to comparison, so that both traces could be superimposed on a common, non-dimensional time axis for the curve-fitting step described next

5.3 Calibration procedure and result

With the time axes reconciled, the extracted 3D mid-span nodal displacement history (exported to MATLAB) was superimposed on the 1D hereditary-damping solution, and μ was swept over a range of candidate values; for each value the discrepancy between the two displacement histories was inspected, and the value giving the closest overall agreement evaluated here

through a semi-automated, iterative comparison of a discrete set of trial values rather than a formal least-squares or gradient-based search was retained. This procedure identified

$$\mu_c = 19.5$$

as the calibrated scale parameter for the GFRP material considered.

As an independent sanity check on the three-dimensional model itself (not on μ), the static, long-time deflection of the loaded beam was compared with the classical closed-form solution for a uniformly loaded beam fixed at both ends,

$$I = \frac{bd^3}{12}, \quad f_{\max} = -\frac{qL^4}{384EI},$$

giving $f_{\max} \approx -0.79$ mm against a steady-state numerical value of -0.77 mm a difference of about 2%, confirming that the three-dimensional model does not contradict elementary strength-of-materials theory.

5.4 Cross-geometry validation

To test whether $\mu_c = 19.5$ is a property of the material rather than an artefact of the particular frame dimensions used to derive it, the calibration was repeated, without adjustment, on a second frame of different proportions (a beam supported on two 7 m columns) built from the same GFRP material. The 1D hereditary model, run with the previously calibrated μ_c , reproduced the corresponding 3D reference response closely, supporting the interpretation of μ_c as a material-level, rather than geometry-level, calibration constant subject to the caveat, discussed in Section 7, that only rectangular hollow and solid box sections of one material have been tested to date.

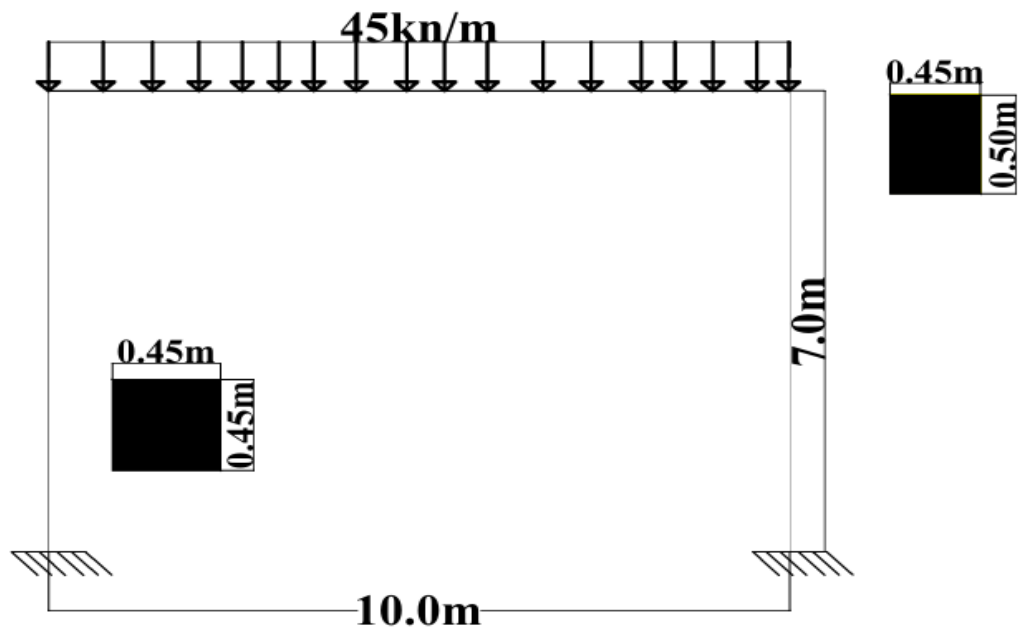


Figure 5 - Scheme of the GFRP 3D solid frame Validatory Analysis implemented in Abaqus Simula

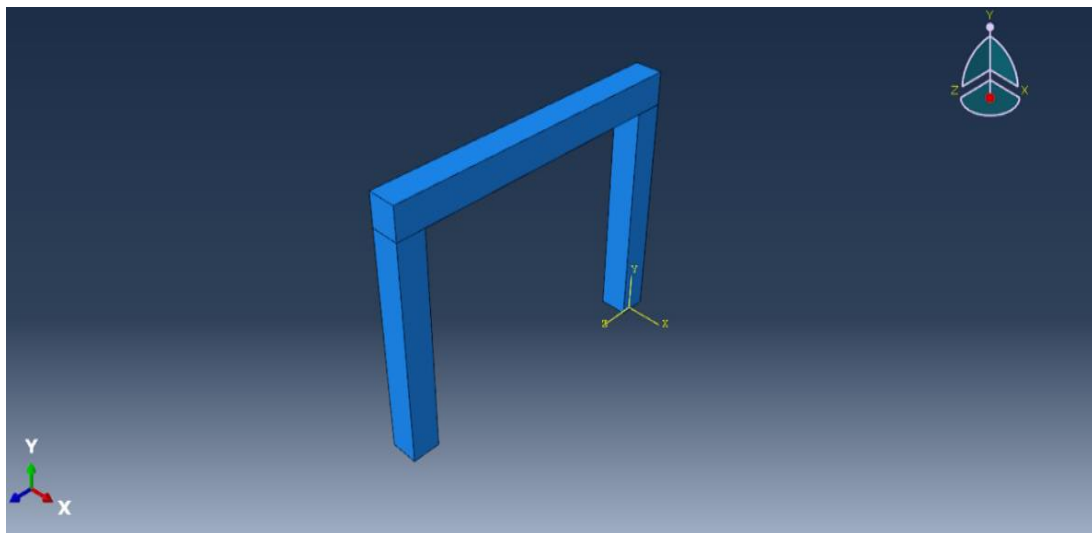


Figure 6 -The 3D assembled model of the validatory example GFRP Solid frame in Abaqus Simula.

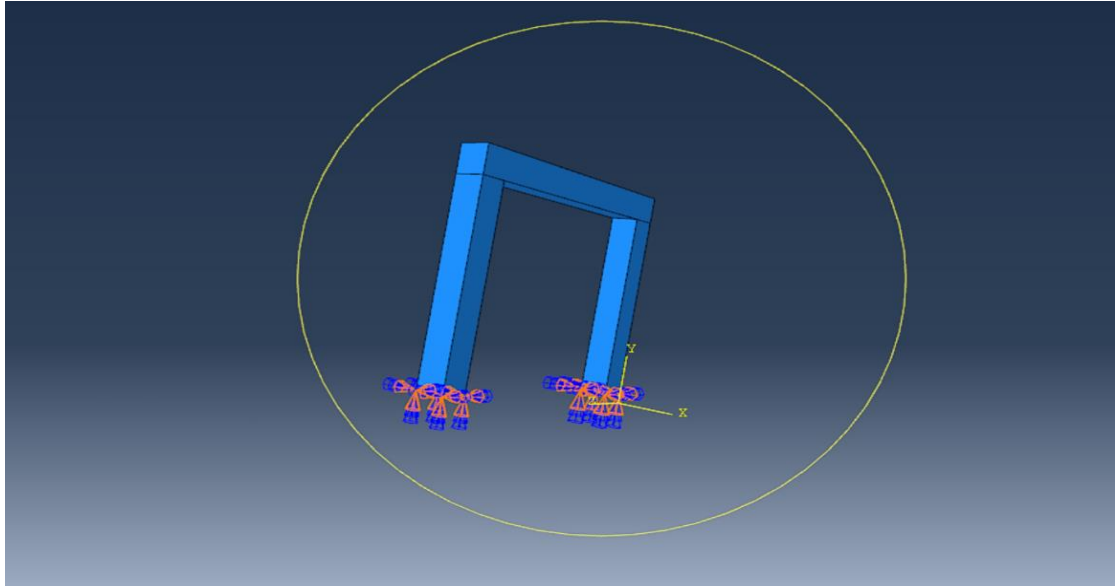


Figure 7- The 3D mesh model of the validity example FRG Solid frame in Abaqus Simula.

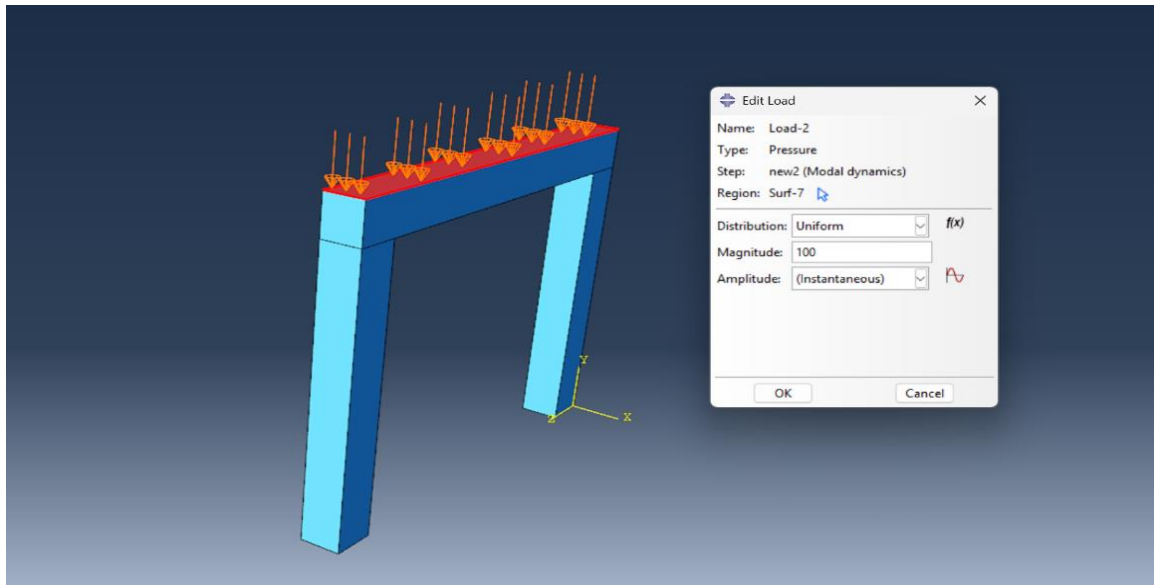


Figure 8-The 3D assembly model of the validatory example FRG Solid frame with pressure loading

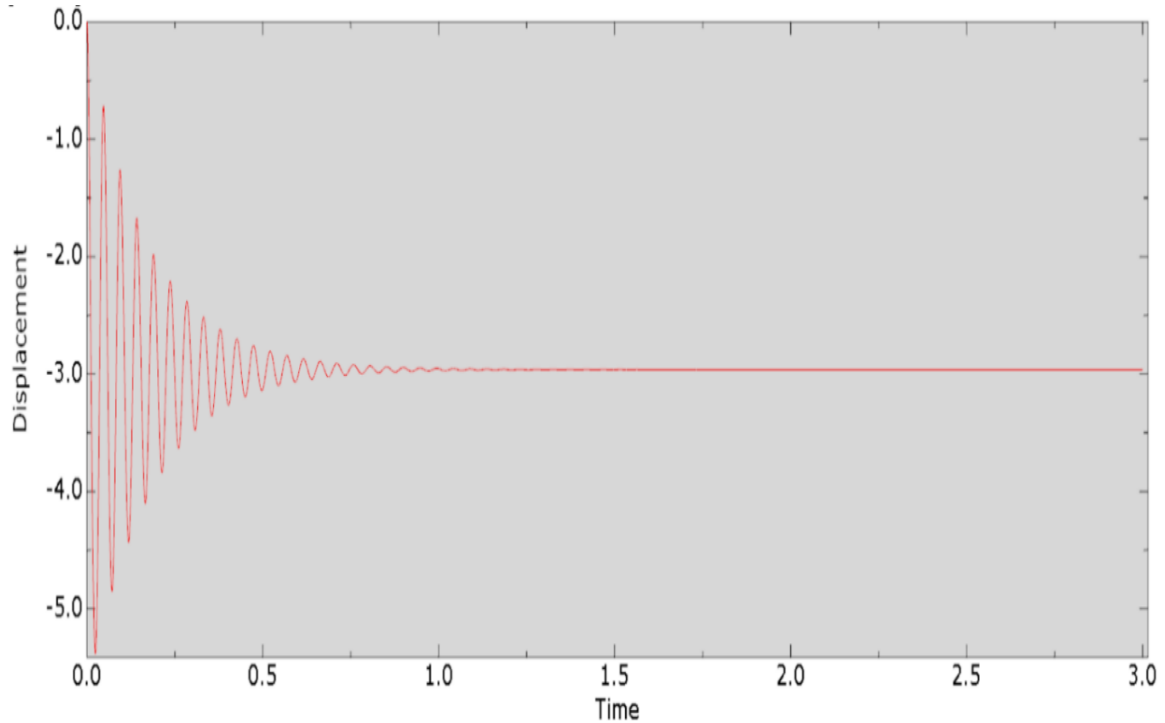


Figure 9 - shows a graph of the central node's displacement over time obtained from the simulation results of frame with changed geometry.

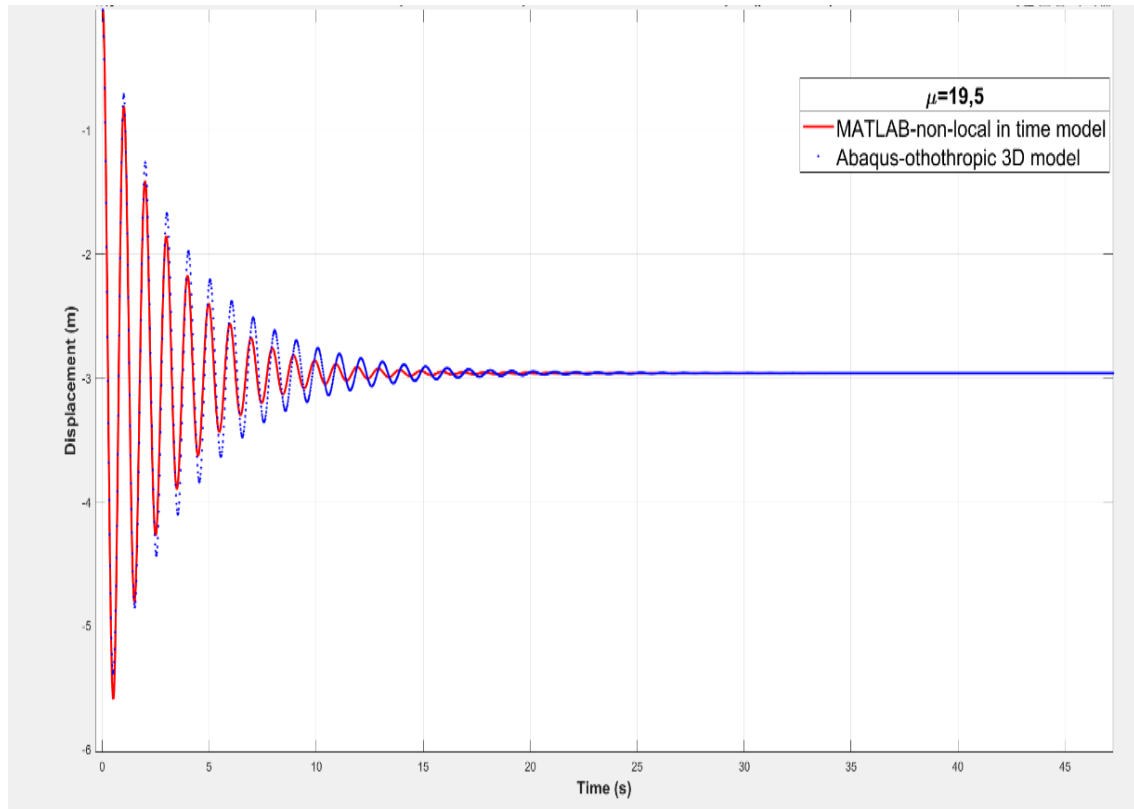


Figure 10 - Confirmation of the scale parameter over a frame with different sectional properties.

6. Seismic response of the calibrated GFRP frame

The calibrated hereditary damping model was used to compute the planar seismic response of the original (9 m beam / 6 m column) GFRP frame under the recorded ground-acceleration history of the 28 March 2025, M_w 7.9 earthquake near Mandalay, Myanmar, applied simultaneously at both fixed column bases. Three cases were compared: two “unscaled”,

effectively local damping cases with $\mu = 100$ and $\mu = 200$, and the calibrated case with $\mu_c = 19.5$. The comparison shows that the calibrated (strongly non-local) model predicts a displacement and velocity response that differs appreciably in both amplitude and the persistence of oscillation after the strong-motion phase of the record from the response obtained with the higher, effectively local values of μ , consistent with the expectation that material memory becomes most consequential precisely during and after the intense, non-stationary phase of strong ground shaking, when the loading history changes rapidly and unevenly.

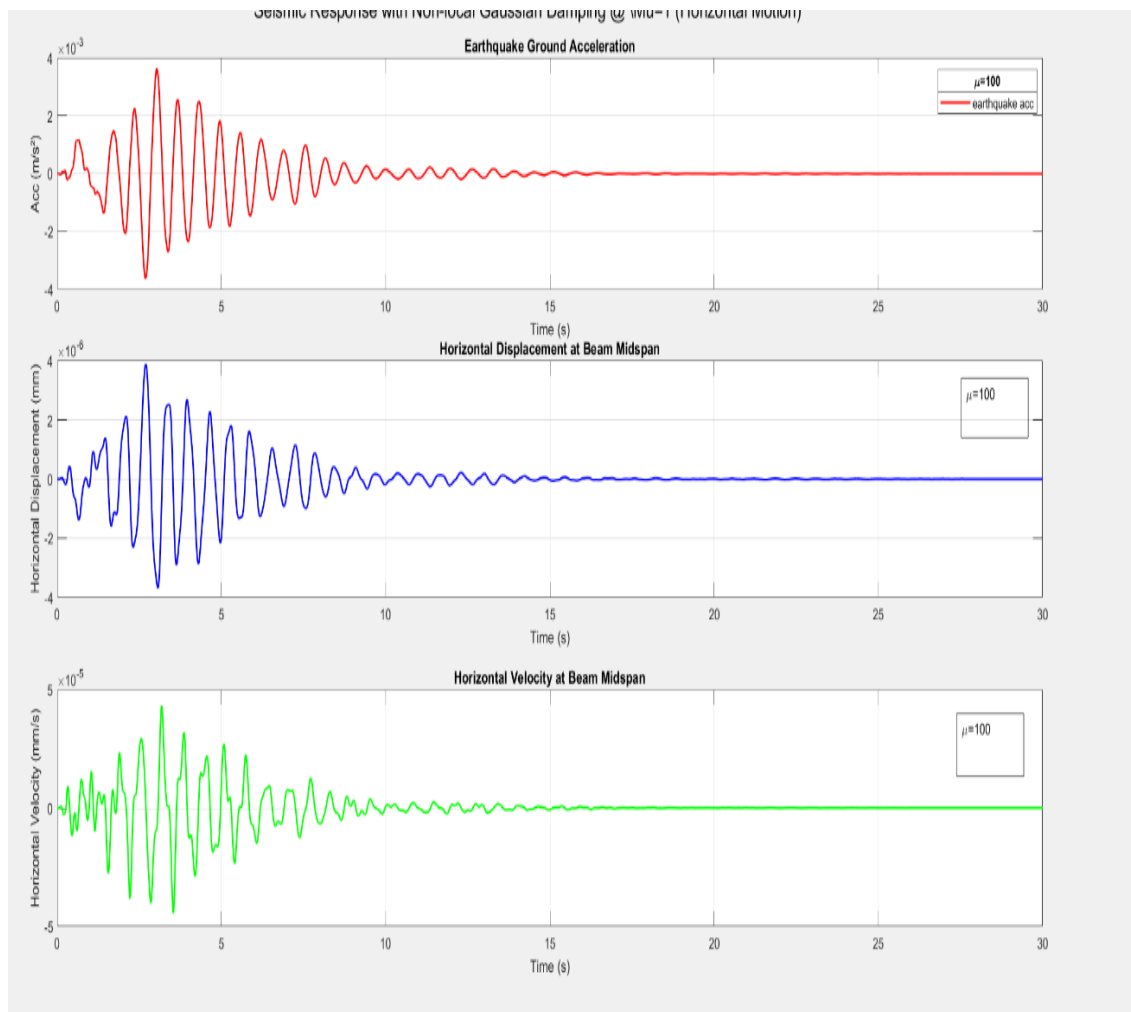


Figure 11 - shows a response on the FRG frame under seismic load application with unscaled parameter- $\mu=100$

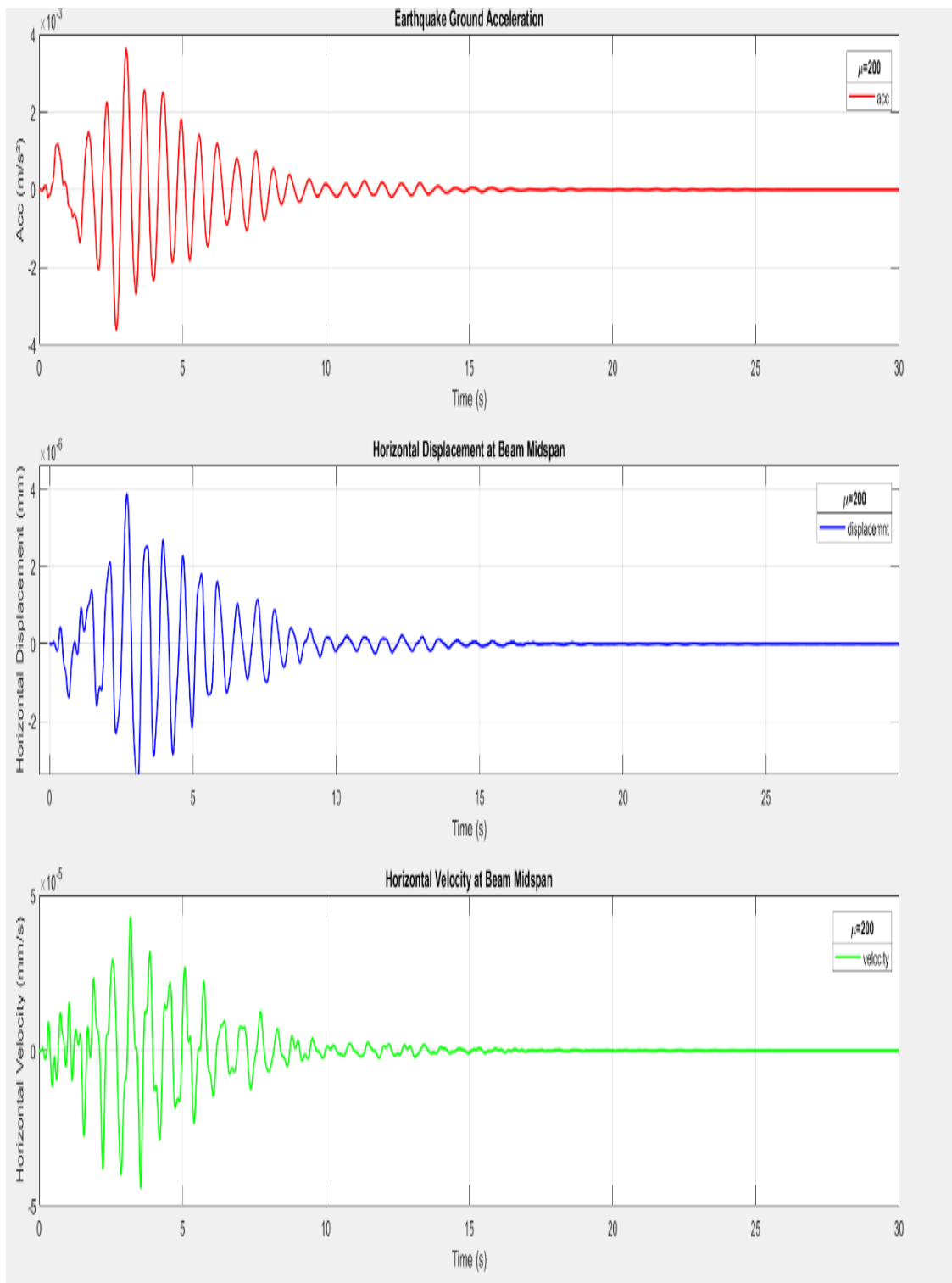


Figure 12 - shows a response on the FRG frame under seismic load application with unscaled parameter- $\mu=200$

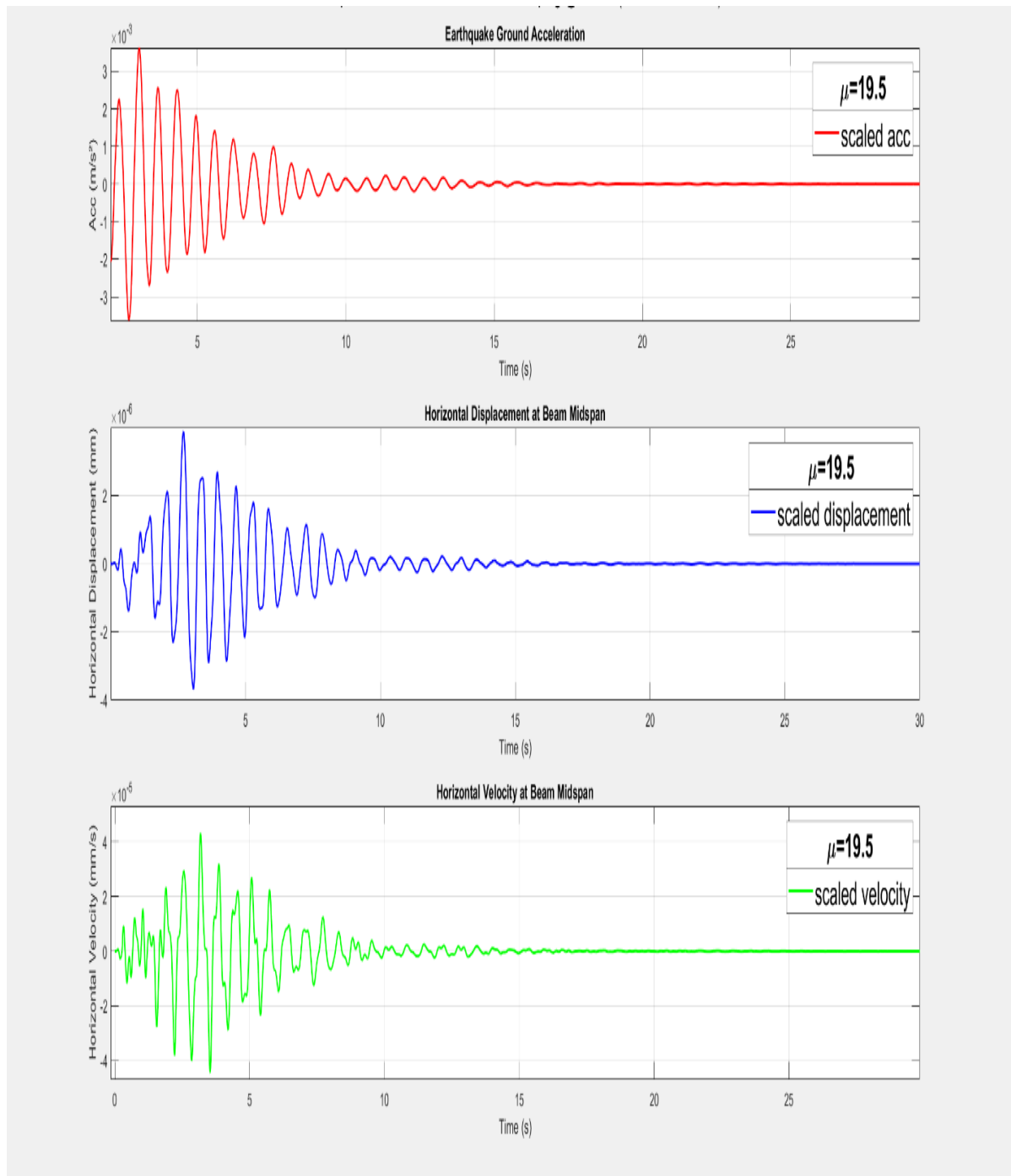


Figure 13 - shows a response on the FRG frame under seismic load application with the scale $\mu=19.5$ obtained from the calibrated 1D and 3D numerical simulation

7. Discussion and limitations

Linearity and planarity. The formulation is restricted to linear elastic material behavior, small deformations, and planar (in-plane) frame motion; large-displacement, nonlinear-material and out-of-plane/torsional effects are outside the scope of the present model.

Single-parameter, single-kernel memory. The hereditary damping model uses one relaxation parameter and one kernel shape (Gaussian). This is the adopted memory-dependent damping representation; a structure combining components with genuinely different relaxation time-scales (e.g., a hybrid steel–GFRP frame) would likely require multiple relaxation parameters, as noted for exponential-kernel formulations in the literature reviewed [10].

Computational cost. As noted in Section 3, the discretized convolution sums β_i in Eq. (11) accumulates over the entire elapsed history at every time step, giving $O(N^2)$ cost for an N -step time history. This is a material practical limitation for long-duration seismic records; sparse or windowed approximations to the convolution sum are a natural avenue for future work; for enhanced computational efficiency relative to full 3D simulation.

Calibration methodology. The identification of μ_c (Section 5.3) was, on the evidence available for this draft, a semi-automated, iterative visual-comparison procedure rather than a formal optimization with a reported goodness-of-fit statistic. IJNME reviewers working in computational mechanics are likely to expect (i) a stated fitting metric (e.g., RMS error or a normalized cross-correlation between the 1D and 3D displacement histories), (ii) some indication of the sensitivity of μ_c to that metric (e.g., a plot of fitting error versus trial μ), and (iii) a discussion of how measurement or modelling uncertainty in the 3D reference solution propagates into uncertainty in μ_c . Strengthening this step is, in the authors’ judgement, the single highest-value revision available before submission.

Scope of validation. The cross-geometry validation in Section 5.4 used a second frame of the same cross-sectional family (rectangular hollow/solid box) and the same material. Generalization to other section shapes (I, T, L, C profiles, mentioned as future work in the source material) and to other GFRP lay-ups remains to be demonstrated.

Novelty relative to prior work by the same research group. The underlying hereditary damping formulation, the Gaussian-kernel choice, and the Newmark–convolution integration scheme was established in prior work by members of this research group for beams and simple rod elements [11]– [14], [17]. The original contribution of the present study is the extension of that formulation to an assembled frame structure, the dual-fidelity (1D–3D) calibration-and-validation methodology of Section 5, and the seismic demonstration of Section 6 not the hereditary damping formulation itself. The manuscript should state this lineage explicitly and prominently (for example, in the closing paragraph of the Introduction), both as a matter of academic accuracy and because IJNME’s stated editorial policy calls for “sufficient original numerical content” and explicitly discourages manuscripts that are framed as an application of existing methods; the calibration methodology, not the frame application per se, is the strongest candidate for the paper’s central claim of novelty and should be foregrounded accordingly in the title, abstract and introduction.

8. Conclusions

A finite element framework for nonlocal-in-time (hereditary) damping, using a Gaussian memory kernel and an implicit Newmark–convolution time-integration scheme, has been assembled for a planar GFRP portal frame and exercised over a range of the governing scale parameter μ . A dual-fidelity calibration procedure, matching the reduced-order 1D response against a full three-dimensional, modal-superposition finite element model of the same frame,

identified a calibrated value $\mu_c = 19.5$ for the GFRP material considered, and this value was shown to transfer, without re-calibration, to a second frame of different proportions. Applied to the recorded ground motion of the 28 March 2025 Myanmar earthquake, the calibrated model produced a displacement and velocity response that differs materially from that obtained using effectively local damping parameters, illustrating the practical relevance of hereditary damping for the seismic analysis of composite frame structures. The proposed calibration strategy offers a computationally efficient alternative to detailed three-dimensional time-history analysis for design-stage seismic assessment of GFRP frame structures, subject to the limitations on linearity, kernel generality, computational scaling, and calibration rigour discussed in Section 7, which the authors are encouraged to address before submission.

CRedit authorship contribution statement

Desmond Iorhemen Abi: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft, Review and editing.

Elena S. Badina: Conceptualization, Supervision, Review & editing.

Abdulakeem O. Ayuba: Investigation and Proofing reading.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

The MATLAB and Abaqus model files, and the Myanmar earthquake acceleration record used, will be made available on request.

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Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During preparation of this manuscript, the corresponding author used Claude (Anthropic), a large language model-based AI assistant, to assist with two clearly bounded tasks. First, the tool was used to condense and restructure source material from the first author's master's thesis into the organization, section structure, and prose of this research article. Second, the tool was used to generate Figures 1 and 3 (the Gaussian memory-kernel plot and the one-dimensional finite-element mesh schematic) programmatically, computed directly from the governing equations and node coordinates supplied by the authors, for illustrative purposes.

The AI tool was not used to generate, run, or analyze any simulation, numerical, or experimental result reported in this paper. All reported results including the calibrated scale parameter $\mu_c = 19.5$, the three-dimensional Abaqus model outputs, and every figure other than Figures 1 and 3 originate from the authors' own thesis work, MATLAB code, and Abaqus models. After using this tool, the authors reviewed, verified, and edited all AI-assisted content and take full responsibility for the accuracy, originality, and scientific integrity of the published work. No AI tool is listed as an author, and no AI tool was granted any rights over the underlying research materials.

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