TIMBER AND COLD-FORMED STEEL HOUSING: STRUCTURAL FIRE BEHAVIOUR AND CLUSTER VULNERABILITY IN THE WUI

Serdar Selamet[1], Marion Charlier[2], Nisha Saharan[3], Negar Elhami-Khorasani[4], Yu Niu[5], Thomas Gernay[6], Maciej Chrzanowski[7], José Humberto Matias de Paula Filho[8]

ABSTRACT

Wildland-urban interface (WUI) fires and urban conflagrations expose low-rise residential buildings to severe thermal conditions. A critical yet insufficiently quantified mechanism of structure-to-structure fire spread is the transition from window-dominated compartment burning to exterior plume-driven burning following structural degradation and breach of the building envelope. This transition does not necessarily coincide with full burnout; structural collapse may occur prior to fuel depletion. Most North American houses are Type V-B light timber-framed, containing large quantities of combustible structural wood, which contributes to high heat release rates and long-duration burning. Cold-formed steel (CFS) framing is non-combustible; however, its thin sections heat rapidly and lose mechanical capacity when exposed to fire. This study presents a comparative structural fire engineering assessment of structurally equivalent timber and CFS residential systems using real building plans, compartment-fire thermal estimation, structural fire response analysis, and spatial risk modelling within a residential cluster assuming a single initially ignited source building. Results indicate that although CFS systems may still suffer irreparable structural damage when ignited, they produce lower radiative exposures at neighbouring buildings and longer times to exceed the ignition threshold compared to timber-framed structures. When reconstruction likelihood is incorporated into embodied-carbon estimates, timber's lower initial carbon footprint may be offset by its higher fire-spread risk under WUI conditions.

Keywords: Wildland-urban interface; WUI, wildfire; cold-formed steel; timber; building fire spread

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[1] Managing Engineer, Exponent,
e-mail: sselamet@exponent.com, ORCID: https://orcid.org/0000-0001-9444-470X
[2] Central Engineering Lead, ArcelorMittal Steligence
e-mail: marion.charlier@arcelormittal.com, ORCID: https://orcid.org/0000-0001-7690-1946
[3] Graduate Student, University at Buffalo
e-mail: nisha@buffalo.edu, ORCID: https://orcid.org/0009-0002-9852-6301
[4] Associate Professor, University at Buffalo
e-mail: negarkho@buffalo.edu, ORCID: https://orcid.org/0000-0003-3228-0097
[5] Graduate Student, Johns Hopkins University
e-mail: yniu11@jhu.edu, ORCID: https://orcid.org/0000-0002-5680-0010
[6] Associate Professor, Johns Hopkins University
e-mail: tgernay@jhu.edu, ORCID: https://orcid.org/0000-0002-3511-9226
[7] Technical Sales Manager, Remagin, Etex Group
e-mail: maciej.chrzanowski@etexgroup.com, ORCID: https://orcid.org/0000-0002-6304-5324
[8] Senior Research Engineer, Global R&D, ArcelorMittal, Luxembourg
e-mail: jose.matias-de-paula@arcelormittal.com,ORCID: https://orcid.org/0000-0002-5768-4023

1 INTRODUCTION

Wildland-urban interface (WUI) fires expose low-rise residential buildings to evolving thermal conditions that may transition from ventilation-controlled compartment burning to exterior plume-driven fire as structural elements degrade and the envelope is breached. Most North American houses are light timber-framed (Type V-B construction), where combustible structural members contribute directly to fire load and sustained burning. Cold-formed steel (CFS) framing, currently used in a limited but growing segment of North American low- and mid-rise residential construction, particularly in fire-prone and code-driven markets, provides a non-combustible alternative structural system but undergoes rapid heating and stiffness degradation under elevated temperatures. The motivation for this comparison is to isolate how structural combustibility itself influences fire severity, exterior exposure, and cluster-level vulnerability. This study presents an integrated framework that couples structural fuel load estimation, enclosure fire simulation, temperature-dependent structural analysis, wildfire-based building-to-building fire spread modeling, and life-cycle embodied carbon assessment to evaluate structurally equivalent timber and CFS residential systems under WUI conflagration scenarios.

2 PROBLEM DESCRIPTION

A representative Type V-B two-story residential building with a total floor area of 215 m² and flat roof is selected as the reference archetype (Figure 1). The footprint and building height are consistent with the Pacific Palisades residential inventory. The structural system consists of conventional light timber framing, including sheathing, studs, joists, and rafters. The total structural wood mass is calculated from volumetric quantities and material density (Table 1), resulting in 9,120 kg of combustible structural material. This mass represents the structural fuel load of the building.

Figure 1. Architectural rendering of the representative two-story residential case-study dwelling.

To normalize the structural fuel load for use in the WUI cluster simulations, the total structural mass is expressed per footprint area. For the two-story configuration, this corresponds to 72.5 kg/m². However, because cluster-level exposure calculations are based on plan-area density rather than total floor area, an equivalent single-story configuration of the same footprint is also evaluated to establish a representative structural fuel load per ground area. The resulting value is approximately 50 kg/m² for a one-story building. For additional stories, the incremental structural mass is conservatively represented as about 25 kg/m² per added level. An equivalent CFS-framed case study building is developed with identical geometry, layout, and structural performance characteristics (Figure 1). CFS residential construction typically employs non-combustible materials such as galvanized steel framing, mineral wool insulation, and gypsum-based boards (Figure 2). Although gypsum boards may include thin paper facings, experimental testing indicates that their contribution to overall fuel load is negligible relative to timber framing systems [1]. CFS wall, floor, and roof assemblies are often designed to achieve fire-resistance ratings [1]; however, to ensure conservative and directly comparable fire spread conditions with the timber case, no credit is taken for fire-rated assemblies in this study.

Table 1. Type V-B Residential House (Archetype) wood mass (structural fuel load).

# of Stories	Length (m)	Width (m)	Wall Height (m)	Ext. Wall Area (m²)	Roof Area (m²)	Total Sheathing Vol (m³) Ext. + Int. + Roof	Total Framing Vol (m³) studs, joists and rafters	Unit Weight (kg/m³)	Total Wood Mass (kg)	Total Wood Mass per footprint area (kg/m²)
2	17.0	7.4	6.60	322.0	169.0	7.25	9.02	560.6	9,120	72.5
1	17.0	7.4	3.90	190.0	169.0	5.67	5.57	560.6	6,299	50.1

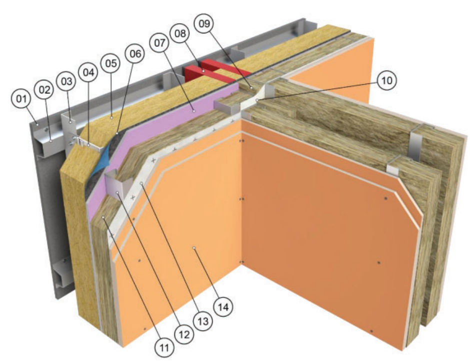


Figure 2. External lightweight wall detail with internal separating wall junction, EU-based solution [1].

3 METHODOLOGY AND RESULTS

Ignition mechanisms in WUI are well studied; however, the influence of structural combustibility on fire severity, external exposure, and cluster-scale vulnerability remains insufficiently quantified. This study presents a comparative structural fire engineering framework integrating enclosure fire simulation, structural response, and spatial fire spread modeling to evaluate structurally equivalent timber and CFS residential systems. The focus is on linking structural fuel load and structural degradation to WUI building-to-building fire risk and reconstruction-driven carbon impacts.

3.1 Building fire modeling

Building fire behavior is represented using enclosure fire dynamics, with emphasis on the duration of the fully developed high-heat release rate (HRR) phase, which governs time-integrated external exposure and relative spread potential in closely spaced WUI clusters (< 10 m separation). The modelling assumes that interior ignition has already occurred in the house as a result of an external fire exposure mechanism (e.g., ember intrusion, flame contact from an adjacent element such as a deck or fence, window breakage, etc.). For wildfire-resistant CFS construction, the probability of sustained exterior-to-interior fire growth is expected to be reduced by design intent (reduced ignitability of exterior assemblies), making an interior fully involved scenario a conservative representation for quantifying potential exposure once ignition has occurred.

Building fire simulations were performed using CFAST, a two-zone compartment fire model developed by NIST, to estimate (i) the hot gas layer temperature and (ii) the incident heat flux at representative window locations for each source building in the selected WUI cluster. Figures 3 and 4 illustrate the HRR input and representative thermal outputs for a single-family residence selected from a Pacific Palisades cluster. The exemplar building has a 183 m² footprint, 4.0 m overall height (one story), and an average 20% window-to-wall ratio across its exterior walls. Each house is represented as a single compartment with plan dimensions matching the building footprint without interior walls. The exterior openings are idealized as eight symmetric window vents (two per wall) to preserve (a) the prescribed overall window-to-wall ratio and (b) approximately uniform vent distribution around the perimeter. Window vents are modeled as a horizontal band with sill height = 1.0 m and vent height = 1.5 m, consistent with typical residential window placement.

Two fuel contributions are defined: (1) dwelling/contents fuel and (2) structural fuel (for timber framing). The dwelling fuel load density is taken as the Eurocode characteristic variable fire load for dwellings, $q_{f,k} = 780\ MJ/m^2$ (per floor area). A combustion factor m = 0.8 is applied to represent incomplete combustion for predominantly cellulosic fuels, consistent with Eurocode EN 1991-1-2. The resulting total dwelling energy is:

$$E_{dwell} = m \cdot q_{f,k} A_f \quad (1)$$

The structural fuel load is taken as the average of the timber case studies listed in Table 1 (i.e., structural wood quantities from sheathing, studs, joists, and rafters). The structural wood mass is estimated as an areal density that scales with the number of stories, and converted to energy using the Eurocode net calorific value of wood (17.5 MJ/kg). For CFS houses, the structural fuel load is considered negligible and therefore set to zero, which is consistent with the premise that the structural framing does not contribute meaningful combustible mass.

CFAST requires the fire to be specified through an HRR history. The input HRR, shown in Figure 3a, is made of a piecewise curve composed of: (i) t^2growth phase, (ii) steady HRR plateau, and (iii) a linear decay phase to burnout. The peak HRR is capped by a fuel-based limit expressed per floor area (here taken as 250 kW/m² per Eurocode). In this implementation, the HRR curve is constructed so that the plateau persists until 70% of the total available energy has been released, followed by a linear decay to represent burnout. Separate HRR objects can be assigned for "dwelling" and "structure" fuels (Figure 3a), allowing direct comparison of timber (contents + structure) versus CFS (contents-dominated) scenarios. A typical compartment fire with high fuel load and intensity, as in Figure 3a, will be ventilation-controlled. Hence, the actual (computed) HRR in CFAST simulation will be lower as it is capped by the oxygen availability provided by the ventilation openings.

Two primary outputs are extracted from each simulation as seen in Figure 3b-c: (i) upper-layer gas temperature, used as a measure of compartment fire severity and duration, and (ii) incident heat flux at window centers, used as the driving exposure metric for building-to-building fire spread calculations in the cluster.

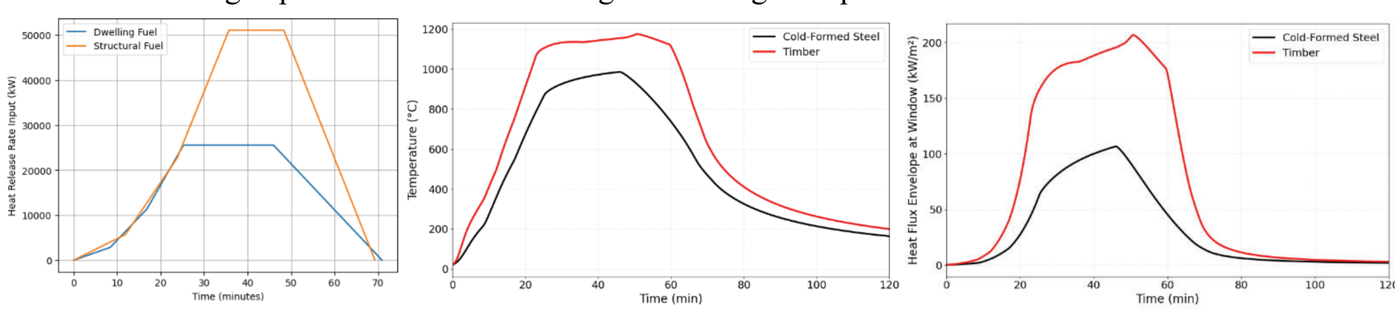


Figure 3. (a) Heat release rate input to represent both dwelling and structural fuel loads, (b) the upper layer compartment temperature-time history and (c) total heat flux (envelope)-time history at the window center.

To compute window heat flux, plate "target" devices are placed at the center of each window slightly inside the compartment and the total incident flux over the simulation is recorded for each window location; the overall window flux is taken as the maximum over all window targets (Figure 3c). In CFAST, a target is modeled as a thin surface that receives both radiative and convective heat transfer from the surrounding gas layers. The reported incident heat flux represents the combined radiative and convective components acting normal to the target surface based on the zone conditions within the two-zone model. The use of window-centered targets is consistent with the goal of estimating radiative/convective exposure at openings that govern external flame ejection and near-field radiation. Relative to the timber case, the CFS scenario exhibits approximately 10–15% lower peak compartment temperatures and nearly 45–50% lower peak window heat flux, reflecting the absence of structural fuel contribution and resulting in substantially reduced external exposure potential.

3.2 Structural analysis

Structural fire analyses are conducted next to inform the time of structural collapse of the house under the interior fire. Structural collapse influences the thermal exposure imposed on an adjacent structure as it suddenly changes the fraction of the HRR that is radiated outward from the burning house. While the building is internally burning but retains structural integrity, the fire regime is akin to a compartment fire and only a limited portion of the HRR is emitted through window openings. After collapse, the fire transitions to a new regime more akin to an external fire (fuel-controlled) and a substantially larger fraction of the HRR can be radiated directly toward neighboring structures. Structural fire analyses to incorporate collapse time in thermal exposure assessments are thus crucial in accurately capturing this mode of structure-to-structure fire spread.

The analysis focused on a load-bearing external wall of the two-story CFS house (Figure 1). The wall on the ground floor is 3.1 m in height, with detail as provided in Figure 2. In particular, the load-bearing components (studs) are S390GD Z275 cold-formed steel-lipped channel sections with dimensions: depth 89 mm, flange 45 mm, lip 12 mm, thickness 1.2 mm. The studs are spaced 600 mm at center; using symmetry only one stud is analyzed. A 2D thermal analysis is conducted in the finite element (FE) software SAFIR using the temperature-time curve from CFAST as thermal boundary conditions. The thermal model is shown in Figure 4. The wall includes a facade panel, a 50 mm cavity, 60 mm of mineral wool, a 12.5 mm plasterboard, an 89 mm stud with mineral wool infill, and a 12.5 mm thick internal plasterboard. The hot flange temperature increases slowly first to 100 °C after 20 minutes, then rises to 750 °C after 50 min.

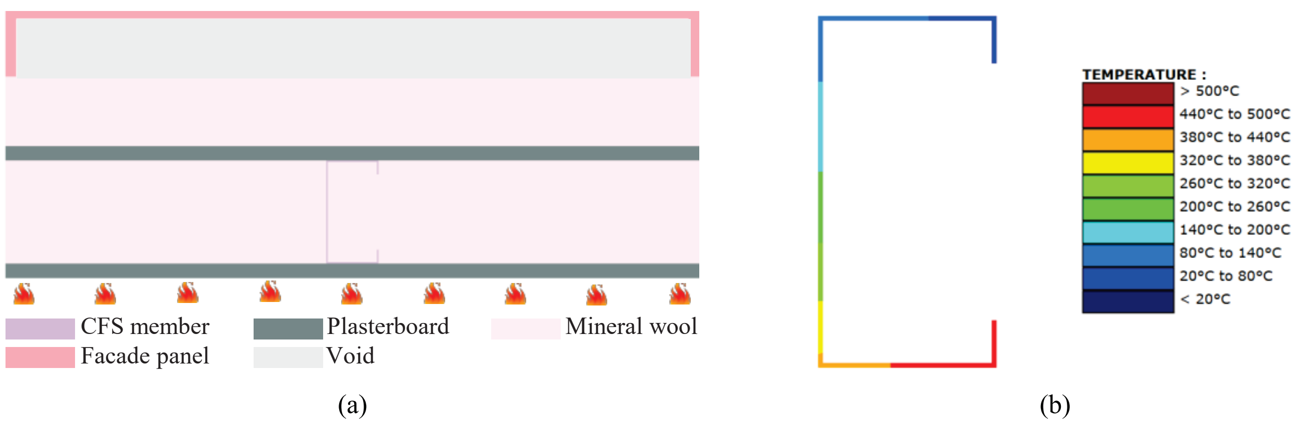


Figure 4. 2D heat transfer analysis of the cross-section of the wall under interior fire – CFS house (a) 2D thermal model and (b) Temperature distribution in the stud after 30 min.

After the thermal analysis, a 3D shell FE analysis was conducted in SAFIR to analyze the thermal-structural response of a wall stud (Figure 5). The 3100 mm long CFS member is discretized with shell elements. The model includes spring elements to represent restraint at plasterboard-to-steel fastener location, and initial geometric imperfections based on elastic buckling modes for local, distortional, and global buckling, adopting the modelling method described in [2]. Two points of fixation are imposed at one-third and two-third of the member length to simulate the lateral bracing. Non-uniform temperature histories from the thermal analysis are transferred to the shell model by applying different shell. TSH files to 'strips' of the stud (Figure 5c), which allows capturing the cross-sectional temperature gradient at each time step. SAFIR captures the effects of material and geometric nonlinearities including thermal bowing. The applied load is based on the ASCE 7 load combination in the fire situation (1.2 x dead load + 0.5 x live load), with nominal values of 7.2 kN for dead load and 7.2 kN for live load. The model predicts structural failure after 24 minutes due to local and distortional buckling of the stud. The asymmetry in distortional buckling is clearly observed with greater displacements of the hot flange (Figure 5a and b); the temperature difference of more than 140 °C between the hot and cold flanges causes non-uniform thermal distortion of the cross-section (Figure 5d). Local buckling occurs in the web, also with slightly larger deformation on the fire-exposed side than that on the unexposed side.

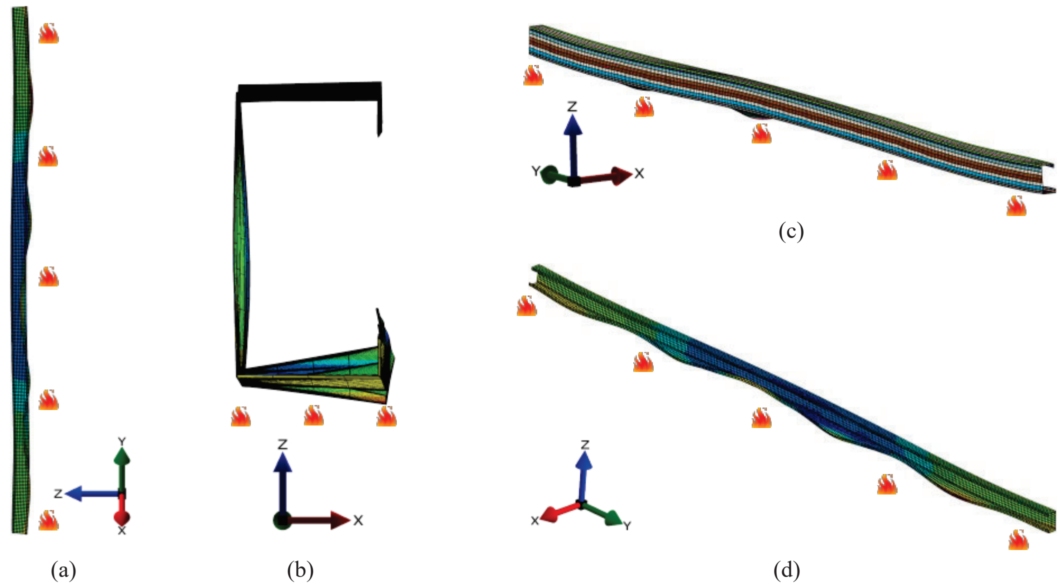


Figure 5. 3D shell analysis of a wall stud under fire at failure – CFS house: (a) front view, (b) side view, (c) temperature distribution, and (d) standard view. Deformations are scaled by a factor 20 in (a), (c), and (d), and by factor 5 in (b).

3.3 Building-to-building fire spread in WUI

To evaluate cluster-scale fire spread potential, a representative group of 18 residential buildings was selected from an area impacted by the 2025 Southern California (Palisades) fires. Building footprints were extracted from geospatial parcel data and building separation distances were computed. Building-to-building thermal exposure is estimated using a simplified radiative point source model. One structure is designated as the source (ignited building), and the incident heat flux at all neighbouring structures is computed as [3]:

$$q''_{target}(t) = \chi_r \frac{\dot{Q}(t)}{4\pi R^2} \tag{2}$$

where R is the separation distance between source and target, and $\chi_r = 0.35$ represents the fraction of total energy released as radiation. To calculate $\dot{Q}(t)$, two approaches are taken to account for structural collapse and uncertainty in flame emission geometry: (1) window-controlled emission (lower bound): as long as exterior walls remain intact, heat emission is assumed to occur primarily through window openings. In this case, the total heat flux history measured at window centres from CFAST is used as the radiative source input. (2) full HRR emission (upper bound): to approximate conditions following wall collapse or large-scale structural failure, the total HRR input to CFAST is used directly in the point source model. This represents an upper-bound exposure scenario in which the full fire power contributes to external radiation. These two assumptions provide lower- and upper-bound estimates of inter-building exposure. Two structural systems are evaluated: (1) timber-framed (contents + structural fuel contribution), (2) CFS framed (contents-dominated fuel load). Radiative exposure is accumulated over time to capture sustained thermal loading. At each time step, a loss/attenuation factor of 0.9 is applied to the previously accumulated value to represent temporal dissipation and avoid unrealistically unbounded energy buildup. The accumulated exposure at 120 minutes is recorded for each target structure. In addition to accumulated flux, the time required for incident heat flux to exceed 14 kW/m² is documented. This value is selected as it is close to ignition thresholds for exterior materials and represents a practical indicator of potential secondary structure ignition [4].

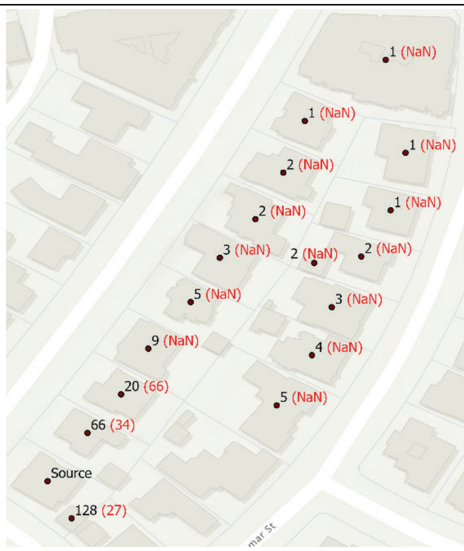
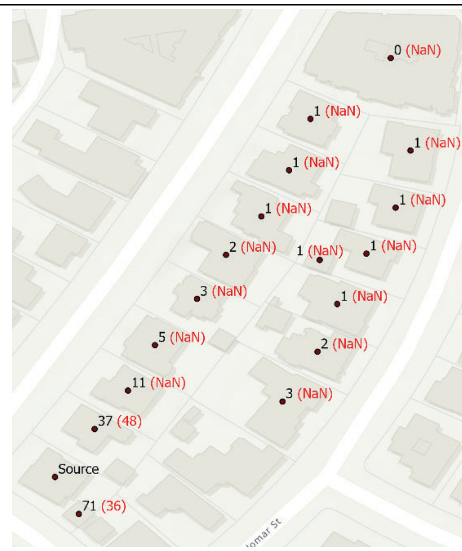
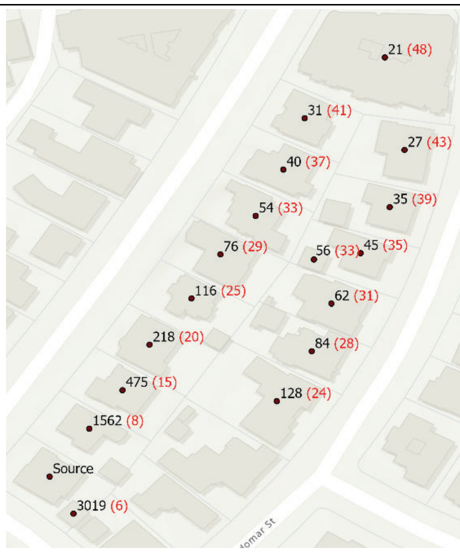
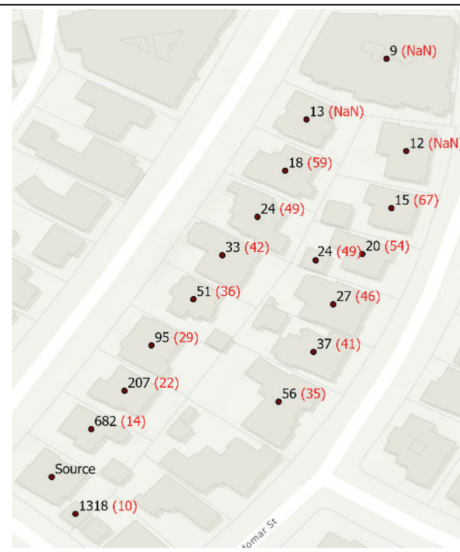
(a) Timber-framed structures	(b) CFS-framed structures
Black values: accumulated radiative exposure [kW/m²], red values (in parentheses): time to exceed 14 kW/m² [min]	
Lower bound	
	
Upper bound	
	

Figure 6. Accumulated radiative exposure received from the source by each building and the corresponding time required for incident heat flux to exceed the ignition threshold (14 kW/m²): (a) timber-framed buildings and (b) CFS-framed buildings.

For building-to-building fire spread, the following are evaluated for each structural system (timber and CFS), assuming one building on fire (i.e., the source): (1) accumulated radiative exposure at neighbouring buildings in the block (i.e., the target), (2) time for incident flux to exceed 14 kW/m², and (3) percentage of buildings within the cluster exceeding the ignition threshold. Figure 6 presents a comparison of building-to-building fire spread for two structural systems, with the selected source building (on fire) located at the edge of the neighbourhood block. Results indicate that incident radiative fluxes generated by timber-framed buildings are approximately twice those of CFS-framed buildings. Correspondingly, the time to exceed 14 kW/m² is longer in the CFS scenarios than in the timber-framed cases, indicating a slower rate of potential fire spread between

CFS structures. While additional ignitions would increase fire exposure in both structural systems, the larger structural fuel load in timber-framed buildings is expected to produce stronger fire growth and greater propagation momentum within the cluster. These findings suggest that CFS structures contribute lower structure-to-structure ignition potential compared to timber buildings, and the longer time required for CFS buildings to reach the ignition threshold may provide additional time for emergency response and suppression.

A larger amount of accumulated radiative exposure is obtained when considering the upper-bound scenario. Thus, the time required to reach the ignition threshold is reduced, with adjacent structures reaching the critical threshold in ten minutes or less, and more distant buildings reaching the ignition threshold, compared to the lower-bound scenario. The structural analysis indicates that CFS failure and subsequent wall/roof collapse may occur after 24 minutes, which delays the transition to a fully open fire; consequently, part of the total heat release is expended before conditions associated with the upper-bound radiative exposures are reached.

3.4 Life-cycle embodied carbon

To assess reconstruction-driven embodied carbon impacts, a life-cycle assessment (LCA) framework is adopted, focusing on cradle-to-cradle modules relevant to structural materials. To date, the only consistent methodology to assess the carbon emissions of a building is a life-cycle assessment (LCA), a science-based and standardized [13, 14] methodology for quantifying and reporting environmental impacts. Although a complete LCA enables an evaluation of the environmental impacts of a building over its entire life cycle, typical building LCAs do not account for resilience or structural robustness because this involves complex scenario modelling. Building LCAs are typically conducted over a reference study period representing the assumed reference service life (RSL) for impact calculations. Exposure to climate-induced extreme events can reduce this lifespan depending on the vulnerability of the structural system and envelope.

In [6], a comprehensive study using LCA was conducted to quantify and compare the quantity of carbon emissions from two commonly designed houses in the Auckland region, one built from timber and the other from light steel framing, both designed for a RSL of 90 years. It was found that the light steel framing house had 12.3% higher GWP in total when compared to the light timber house, of which the material and product manufacturing of two houses had a difference of 50.4% in terms of carbon emissions. The cradle-to-cradle GWP results of this LCA (provided in Table 2) are used in this paper to evaluate the evolution of GWP assessment when accounting for houses burned down in residential neighbourhood. A cradle-to-cradle LCA covers all the life stages of construction: the production of the materials and products (modules A1–A3), the construction process (modules A4–A5), the use of the building (modules B1-B6), the end of life (modules C1–C4), and the net benefits and loads beyond the system boundary (module D) [5].

Table 2. GWP of the two houses investigated from [6]

	A1-A3	A4-A5	B	C	D	
House type	Production stage	Construction stage	Use stages	End-of-life stages	Reuse & Recycling Potential	Total
	kg CO_2e/m^2/year	kg CO_2e/m^2/year	kg CO_2e/m^2/year	kg CO_2e/m^2/year	kg CO_2e/m^2/year	kg CO_2e/m^2/year
Timber	2.31	0.49	11.02	0.64	-0.74	13.72
Steel	4.66	0.31	11.71	0.27	-1.53	15.42

Let's assume a cluster of X houses, with Y and Z being the ratio (in %) of burned timber and steel houses, respectively, and with RSL being the reference service life (considered to be 90 years in the frame of [6]). Given our focus on structural vulnerability and cluster level exposure to WUI fires, the equations (3-4) represent a proposal to account for partial loss of residential units in the cluster LCA. They use the GWP from the Table 2 as inputs, with subscript referring to the house design (timber of light steel framing) and to the LCA module(s). The logic is to account for the complete reconstruction of a house that would be burnt down.

The contribution of the house lost to fire is made accounting for life-cycle stages A (production and construction stages) and C (end-of-life stages) while the contribution of the rebuilt house also accounts for life-cycle stage D (net benefits/burden beyond life cycle such as recycling). Life-cycle stage D is not considered for the house lost to fire as the materials are considered as destroyed, except for steel elements which can still be recycled (represented by $GWP_{[D*],steel}$ in GWP_{steel} which represents -0.8 kg $CO2_e/m^2$/year). Life-cycle stage B, covering maintenance and replacement, operational energy use and operational water use is disregarded in this assessment, as we focus here on the constitutive elements of the house (and as life-cycle stage B is highly dependent on the energy grid mix, here from New Zealand).

$$GWP_{timber} = GWP_{[A+C+D]\,unburned} + GWP_{[A+C]\,burned} + GWP_{[A+C+D]\,rebuilt}$$
$$= RSL\,.\left(X.\left(GWP_{[A],timber} + GWP_{[C],timber} + GWP_{[D],timber}\right) + Y.X.\left(GWP_{[A],timber} + GWP_{[C],timber}\right)\right) \quad (3)$$
$$GWP_{steel} = GWP_{[A+C+D]\,unburned} + GWP_{[A+C+Dsteel]\,burned} + GWP_{[A+C+D]\,rebuilt}$$
$$= RSL\,.\left(X.\left(GWP_{[A],steel} + GWP_{[C],steel} + GWP_{[D],steel}\right) + Z.X.\left(GWP_{[A],steel} + GWP_{[C],steel} + GWP_{[D*],steel}\right)\right) \quad (4)$$

Depending on the fire loss rates, the GWP comparison assessment evolves. In case of 65% and 30% losses for the timber and light steel clusters, respectively, the GWP results become equal. Figure 7 provides combinations of loss ratios leading to the same conclusion.

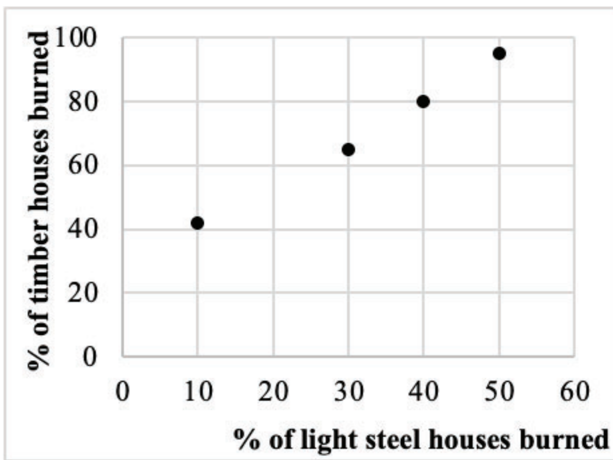


Figure 7. Combinations of loss ratios with similar cluster-level GWP regardless of structural system, derived from [6] data.

This assessment constitutes an initial, approximative step toward a comparative LCA and is subject to several limitations. Notably, when accounting for the GWP of houses destroyed by fire, life-cycle stage C1 (demolition) should be omitted, as fire damage is assumed to eliminate the need for selective demolition. In contrast, life-cycle stages C2–C4 (waste transport, recycling or disposal, and final disposal) remain relevant even under fire scenarios. It should be noted that building-related GWP cannot be generalized, as it depends on various factors, including material composition, geographical context, and the selected time horizon. For example, the residential units assessed in [15] are located in New Zealand rather than California, and their designs are expected to differ in terms of structural loads, climatic conditions, and regulatory requirements.

This is why in the next phase of this work, a cradle-to-cradle LCA will be conducted to evaluate the GWP of the two equivalent houses designed within the scope of this study and described in Section 2. Future refinements should also integrate recent decarbonization developments in the steel industry (such as the increased availability of coils produced via Electric Arc Furnace) which affect the selection of Environmental Product Declarations and will reduce the GWP of CFS-based buildings. Furthermore, the present study employs a binary classification of houses as either burned or unburned, based on the proportion of buildings within the cluster exceeding the ignition threshold.

4 CONCLUSIONS

This study developed and applied an integrated framework that links structural fuel load, compartment fire dynamics, structural collapse behavior, and wildfire-style radiative exposure modeling to evaluate structure-to-structure fire spread in WUI.

- Timber archetypes, with structural fuel loads on the order of 50 kg/m² (one story), produced longer burning durations and about twice the incident radiative flux at neighboring buildings compared to CFS cases.
- Structural analysis of the CFS wall stud predicted failure at approximately 24 minutes, demonstrating that collapse timing governs the transition from window-controlled emission to a more open, externally radiating fire regime, consequently, cumulative exposure is expected to lie between the lower- and upper-bound scenarios presented in this study.
- Cluster simulations with a single ignited edge building showed that timber structures lead to shorter times to exceed the 14 kW/m² ignition threshold and a larger fraction of secondary ignitions relative to CFS.
- When reconstruction due to fire loss is incorporated into a life-cycle embodied carbon framework, timber's lower initial GWP advantage can diminish or reverse under sufficiently high loss ratios.

The proposed framework represents a first-order, comparative assessment and is subject to several simplifying assumptions. Building loss is treated in binary form (burned/unburned) without explicit modeling of partial damage states, and operational emissions (life-cycle stage B) are excluded to focus on structural and reconstruction impacts. Post-fire end-of-life stages and fire-resistive assembly contributions are simplified, and the cluster analysis considers a single initial ignition scenario. In addition, the LCA inputs are based on published New Zealand case-study data and are used here illustratively; region-specific material sourcing, regulatory conditions, and design practices may influence absolute GWP values. The thermo-mechanical structural analysis was conducted explicitly for the CFS system to estimate collapse timing and illustrate its influence on the transition between fire regimes; a corresponding detailed heat transfer and structural analysis of timber framing was not performed within the present scope. For timber-framed buildings, structural degradation is represented indirectly through the structural fuel contribution to the HRR curve and the upper-bound exposure scenario. These assumptions do not alter the comparative trends observed but indicate areas for future refinement. Future work will extend the framework to include region-specific cradle-to-cradle LCAs for the developed archetypes, explicit thermo-mechanical analysis of timber systems, multiple ignition and collapse sequences within clusters, and a more direct coupling between time-to-collapse and the evolution of $\dot{Q}(t)$to better represent realistic post-wildfire fire progression and recovery scenarios.

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