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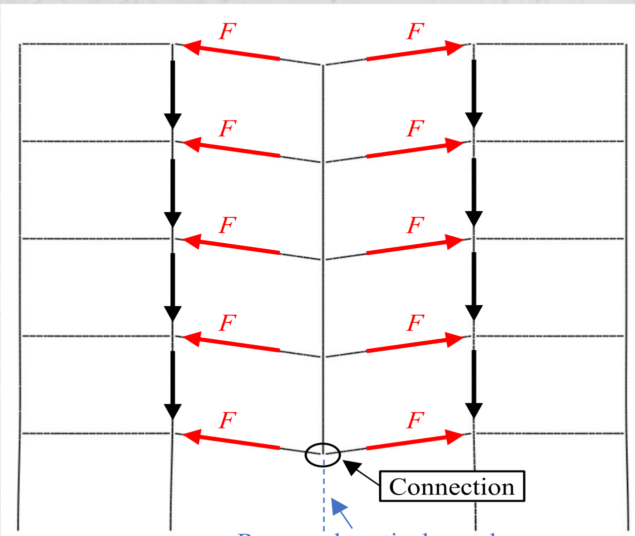
PROJECT #24: NEXT GENERATION OF ROBUST AND FIRE-RESILIENT LIGHT GAUGE STEEL SYSTEMS FOR MID-RISE BUILDINGS

FINAL REPORT EXECUTIVE SUMMARY



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Australian Government
Department of Industry, Science and Resources
Cooperative Research Centres Program

CONTENTS

CONFIDENTIAL:	☐ Yes X No
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Date of this report:	31/08/2025
Project completion date:	31/07/2025
Program Leader reviewer:	Tuan Ngo and Mahen Mahendran
Project title:	**Project #24: Next Generation of Robust and Fire-resilient Light Gauge Steel Systems for Mid-Rise Buildings**
Project duration:	3 years
Partners:	• BlueScope • NASH National Association of Steel Framed Housing • The University of Melbourne • Queensland University of Technology
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Ethics approval details (if relevant)	Not applicable

1 EXECUTIVE SUMMARY

Light gauge steel (LGS) offers several advantages over other materials in mid-rise construction, including good strength to weight properties, ability for pre-fabrication leading to quicker construction times, non-combustibility, and resistance to rotting, shrinking, warping and termite attack. For a LGS solution to be a viable alternative to timber, hot rolled steel and other structural systems, particularly in mid-rise building applications, it needs to be considered early in the design phase. However, it is not clearly understood what tools and inputs are utilised in the early stages of design. These unknown challenges and barriers to the adoption of LGS in the Australian mid-rise building market are a key industry problem. Specifically, developers require a demonstration of 15% savings to instil confidence in the replacement of conventional systems, such as reinforced concrete, with LGS. Furthermore, savings will vary for different project types and locations. Several factors need to be considered to achieve this, such as fitness for functional requirements (structural, fire, thermal, acoustic) and understanding of the supply chain.

Robustness to progressive collapse is a critical concern in LGS systems, particularly given that the connections in LGS buildings are usually in the form of screws and rivets with low tying resistance. Fire resistance of LGS floors is another critical concern as current Fire Resistance Levels (FRLs) are based on limited proprietary fire test data and/or expert opinion relevant to conventional systems. These issues need to be addressed to allow a more widespread adoption of LGS structures in the mid-rise construction market, which also includes office buildings, apartments, hotels, hospitals, student accommodation and aged care facilities. The Building 4.0 Cooperative Research Centre Project 24, therefore, focused on addressing the above-mentioned industry problems via two sub-projects:

1) Design for resisting progressive collapse for mid-rise light gauge steel buildings
2) Fire resistance of light gauge steel floor systems.

Both sub-projects are briefly described and findings outlined in this Executive Summary. More extensive detail can be found in the individual sub-project reports.

1.1 SUB-PROJECT 1: Design for resisting progressive collapse for mid-rise light gauge steel buildings

Building collapses can result in the catastrophic loss of human life and have correspondingly negative economic and social impacts. Building collapses are often characterised by the cumulative propagation of local failures triggered by extreme or abnormal events. With the predicted increasing frequency of extreme weather events, it is important to design buildings that prevent such progressive collapse. Given the previously described advantages of LGS, detailed design provisions to increase robustness are particularly important if there is to be an increase in the construction of LGS buildings i.e. enhanced building strength to prevent progressive collapse.

Structural connections in mid-rise LGS buildings play an important role in load redistribution after removal of several vertical members as a result of an extreme event e.g. a stud wall in the building. Traditional connections are designed to resist shear and bending moment, thereby losing resistance in tensile load. As appreciable tensile load is induced after stud wall removal, it is important to enhance the robustness of connections, particularly the tensile resistance of connections, to prevent premature damage that could lead to progressive collapse.

Sub-project 1: Robustness focused on a solution to the above-mentioned problems, specifically, by increasing the robustness of both component connections and mid-rise LGS framed buildings more generally. The connection behaviour was investigated experimentally, numerically and theoretically. A series of experiments were conducted to assess the robustness performance of both traditional (clip angle connections assembled with self-drilling screws) and proposed new connection configurations. Based on the test results, a new bottom plate structural component was introduced to connect bottom flanges of adjacent joists. This additional element was found to significantly improve the tensile resistance and overall robustness of the connections in mid-rise LGS buildings. Finite Element (FE) simulations were then performed to gain deeper insight into structural behaviour not observed during the physical experiments. These simulations were based on a proposed simplified FE modelling approach designed to accurately represent the response of screws under both tension and shear loading. Additionally, a comprehensive parametric study was employed to identify the key factors influencing connection performance, thereby providing design optimisation strategies. Finally, a theoretical/mechanical model was proposed to calculate the design robustness (tensile force resistance) of the proposed new connection. The model is suitable for both concentrated and distributed loads and can be conveniently implemented using hand calculations, providing practical benefits for engineering design.

The robustness of the entire building system was also investigated through numerical simulation and theoretical analysis. An archetype mid-rise LGS building was first designed, considering gravity and wind loads. The building consisted of eight stories, each comprising ten rooms connected by a central corridor. Numerical analysis of the archetype building was then performed under four stud wall removal cases, in accordance with the National Construction Code (NCC). Due to the complex configuration of the archetype building, a simplified FE model was developed to reduce computational costs while maintaining accuracy. This model incorporated simplified simulation methods for all connection types and structural members commonly used in mid-rise LGS buildings, as well as an appropriate damping ratio to simulate dynamic effects. The simulation results showed that the removal of a stud wall at the ledger can result in significant load transfer to the adjacent remaining studs. Additionally, the influence of the floor system and load-bearing walls on overall building robustness was examined. The findings suggested that while the floor system had a minor effect, the presence of bearing walls increased the structural robustness. Based on the FE results, a theoretical framework was proposed to evaluate the critical parameters including the dynamic affected area, dynamic increase factor and the revised tributary area after stud wall removal.

Main Findings of Sub-project 1

- The strength of the ledge-joist connection, specifically the screwed clip angle connection, was examined through tests on nine cold-formed steel ledger-joist connections. A parametric study was further conducted to investigate the influencing factors on the connection strength, using finite element (FE) simulations based on the validated model.
- A simplified FE simulation method was proposed to streamline the modelling of screws, reducing computational complexity.
- A new connection was introduced to enhance the connection robustness. Its performance was evaluated using six sub-assembly specimens. Based on the experimental findings, a bottom plate was proposed as a new element for joist-to-joist connections to enhance tying force, termed the joist-to-joist bottom plate connection.
- A hand calculation method was developed to determine the tying force of buildings, incorporating the newly proposed connection.
- The overall robustness of the building was assessed using a simplified FE model of a newly designed archetype load-bearing wall LGS buildings. Four distinct stud wall removal scenarios were analysed, and dynamic increase factors (DIFs) were proposed for each scenario with varying removal times.
- Based on the numerical analyses of the building, a hand calculation method was established for designing mid-rise load-bearing wall LGS buildings to resist progressive collapse.

1.2 SUB-PROJECT 2: Fire resistance of light gauge steel floor systems

Conventional LGS framed floor systems comprise a single row of thin (<3.0 mm), high strength (450-550MPa) cold-formed steel (CFS) lipped channel section joists or C-sections or top hat trusses connected to flooring made of timber boards or fibre cement boards, protected by one or two layers of fire-rated gypsum plasterboard on the ceiling side, with or without cavity insulation. However, fire can rapidly deteriorate the strength and stiffness of light steel members when gypsum plasterboard ceiling is compromised during a fire event, which can lead to a catastrophic failure. Suitable ceiling, flooring and insulation configurations are needed to keep the temperature rise in both the channel joist/truss and the unexposed flooring side within accepted safe limits during fires. Such configurations delay structural, integrity and insulation failures and provide the required Fire Resistance Levels (FRL) of floors e.g. 120/120/120 min for office buildings. However, there have been limited studies of the behaviour and design of high strength LGS floor systems under ambient and fire conditions, specifically in an Australian context. Fire design of LGS floors is critical to the uptake of this otherwise viable structural alternative. However, currently the FRLs are based on limited fire test data obtained for LGS floors made of low strength steels and proprietary board products, and/or expert opinions.

This sub-project focused on addressing these specific industry problems and research gaps through two studies on the performance of LGS joist and truss floor systems under ambient and fire conditions. Each study included material property tests at ambient and elevated temperatures, ambient temperature and standard fire tests, and advanced heat transfer and structural finite element (FE) modelling to obtain practical insights and accurate FRLs of LGS floor systems.

Further, robustness of LGS buildings in fire was also assessed when non-fire rated floor/roof systems are used with fire-rated load-bearing wall systems or when unprotected combustible electrical sockets and service pipes are used within wall systems. In this case (third study), fire tests of small-scale wall assemblies and numerical studies were conducted to investigate their effects on the fire behaviour and FRLs of load-bearing LGS walls.

<u>*The first study*</u> examined the fire behaviour of high strength lipped channel joist floors sheathed with fibre cement board flooring and fire rated gypsum plasterboard ceiling. The study included:

1. material property tests of two common non-combustible fibre cement board floor panels to determine their ambient and elevated temperature thermal properties
2. seven tests of short-span (1.67 m) floors made of two joists with varying ceiling configurations under ambient and fire conditions
3. development and validation of heat transfer and sequentially coupled structural finite-element (FE) models of tested short-span floors to predict reliable FRLs
4. five standard fire tests of full-scale (4.1 m span) channel joist floors with varying ceiling and floor configurations
5. development and validation of heat transfer and sequentially coupled structural FE models of tested full-scale joist floors to predict the fire behaviour and failure times (FRLs)
6. parametric numerical studies using the validated FE models to determine the FRLs for 378 combinations of 18 joist sections and three ceiling configurations (2×13 mm, 2×16 mm, 3×16 mm gypsum plasterboards)
7. fall-off behaviour of gypsum plasterboards based on six full-scale fire tests conducted in this study and 50 previously conducted fire tests to develop simple empirical methods for predicting the plasterboard fall-off times for given ceiling plasterboard configurations.

<u>*The second study*</u> examined the fire behaviour of high strength truss floor systems made of steel top hat and C-section minor axis sections sheathed with fibre cement board flooring and fire rated gypsum plasterboard ceiling. This study included:

1. ambient and elevated temperature mechanical property tests of fibre cement board flooring and gypsum plasterboards
2. eight ambient temperature structural tests of short-span truss floors and associated FE modelling to investigate the complex truss behaviour and review suitable design methods
3. three fire tests of short-span truss floors made of two top-hat and minor axis C-sections with two or three layers of 16 mm fire rated plasterboard ceilings
4. two full-scale fire tests of truss floors with two and three 16 mm plasterboard layers and cavity insulation
5. development and validation of heat transfer and sequentially coupled structural FE models of short-span and full-scale truss floor systems

6. parametric numerical studies using the validated FE models to determine the FRLs for 504 combinations of truss floor systems with varying geometry, thickness and number of layers of gypsum plasterboard, cavity insulation and flooring material.

The third study investigated the effects of using non-fire rated floor/roof to wall connections and combustible electrical sockets and service pipes on the behaviour and FRLs of load-bearing LGS walls. This third study included:

1. two small-scale fire tests to investigate the effects of unprotected combustible electrical sockets
2. two small-scale fire tests to investigate the effects of combustible service pipes
3. one small-scale fire test and associated heat transfer and sequentially coupled FE modelling to investigate the effects of non-fire rated floor/roof-to-wall cleat connections
4. one small-scale fire test and associated heat transfer and sequentially coupled FE modelling to investigate the effects of non-fire rated floor/roof-to-wall connections with steel bearers and cleats.

Main Findings of Sub-project 2

Overall, the first two studies significantly improved the knowledge and understanding of the behaviour of LGS floor systems under ambient and fire conditions, and suggested practical design guidance. Similarly, the third study provided new knowledge and understanding of the fire resistance of load-bearing LGS wall systems when they are (1) attached to floor/roof systems using non-fire rated cleat or bearer and cleat connections, or where they (2) inadvertently include unprotected combustible electrical sockets or service pipes. The main findings are as follows:

- Ceiling protection is paramount. Using multiple- layers of fire-rated gypsum plasterboard in the ceiling is the most effective way to meet FRL requirements. For example, two layers of 16 mm fire rated gypsum plasterboard will typically achieve a 90 min FRL, while adding a third raises it to ~120 min.
- Plasterboard fall-off governs joist/truss failure. The time when the ceiling lining falls off is critical. After fall-off, unprotected steel joists/trusses heat up rapidly. Empirical formulae developed in this study allow the prediction of fall-off time (and hence FRL) based on ceiling configuration.
- Type of joist/truss or flooring material (plywood or fibre cement board) has negligible impact on FRLs. This implies that the FRL is independent of the type of joist/truss and conventional flooring material for a given ceiling configuration.
- Short-span fire tests are an effective way of determining the FRLs as the test results were comparable (though slightly conservative) to full-scale test results. Thus, it is recommended that short-span fire tests can be utilised to obtain the FRLs of LGS floor systems.
- Advanced FE models of LGS floor systems were validated against test results. This study developed heat-transfer and structural FE models under ambient and fire conditions (including imperfections and plasterboard fall-off behaviour). Verified models enabled large-scale parametric studies. By using these tools, engineers can predict the FRLs of new floor configurations with confidence, reducing reliance on testing. For design, it is recommended that analysis includes the thermo-mechanical degradation of LGS floor components and plasterboard fall-off mechanism.
- CFS design standards, such as AS/NZS 4600, provide conservative capacity and FRL predictions for LGS floor systems.
- Plasterboard manufacturer-provided FRLs do not consider the critical parameters identified in this study, such as the load ratio, truss configuration, depth variations, flooring types and cavity insulation. Furthermore, manufacturer recommendations for two and three layers of 16 mm plasterboard were significantly more conservative compared to the study's findings with respect to joist/truss spacing (450 mm to 600 mm) and FRLs (60 min to 90 min).

- Effects of unprotected combustible electrical sockets and service pipes and non-fire rated floor/roof-to-wall connections were shown to be mainly localised high temperatures in the regions near where they were located. In general, they were shown to have minimal impact on the FRLs of load-bearing LGS walls, demonstrating the robustness of LGS construction. However, reassessment of their FRLs and the need for protecting them are recommended.

Overall, the findings from this study not only enable fire safety designers to optimise LGS floor system designs, but also contribute to the National Construction Code (NCC), particularly Part 1, Section C. The comprehensive findings and recommendations of FRLs provided by this research can now be effectively employed to ensure compliance and enhance structural safety across various building classes employing LGS floor systems. Our previous research conducted on the fire behaviour of LGS wall systems was reviewed and the essential FRL data and design methods have also been summarised. They will all be utilised by Project #24 industry partners, National Association of Steel Framed Housing (NASH) and BlueScope Steel, in preparing and publishing the proposed Fire Design Handbook for use by fire design engineers of LGS buildings. Our advanced fire research studies have enabled efficient utilisation of light steel floor systems in mid-rise buildings.

In summary, Project #24 has addressed the two critical concerns related to LGS buildings, their robustness to progressive collapse and fire resistance of LGS floors, using extensive experimental and numerical studies. The many valuable outcomes from this project can be used by the building industry to enable the widespread adoption of LGS structures in the mid-rise construction market such as offices, apartments, hotels, hospitals, student accommodation and aged care facilities.

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