Overview of seismic design of building services in prefabricated frames

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Abstract:

Non-structural components within buildings are those components that are not designed to be a part of the structural force-resisting system; however, they should not pose a threat to inhabitants of structures, and some may be required for continued safe operation or habitation of a facility. To achieve this, a typical approach is to design additional bracing systems to non-structural components' supports. Prefabrication solution are another method to minimise damages from a seismic event by integrating all the requirements of non-structural components, including seismic and gravity supports, into the prefabricated frames.

In this paper, different types of prefabricated frames, their lateral resistance system and seismic performance, which are common in the building services industry, will be discussed. Design loads that need to be considered in the design stage will be identified. Finally, discussion will be presented on how using prefabrication solutions in non-structural components' supports can be beneficial to builders, consultants, and contractors in Australian market in relation to factors such as safety, cost, quality and sustainability.

Keywords: Seismic design, Non-structural component, Prefabrication

1 Introduction

Seismic behaviour of non-structural components (NSCs) in buildings has been under investigation in recent years. Parameters such as damages, economic loss, life safety concerns and loss of operational continuity due to inadequate protection of NSCs during seismic events have been investigated thoroughly. The NSCs within a building that is post-disaster facility (importance level 4 buildings) need to remain serviceable for immediate use, special study is to be carried out to satisfy this requirement. Serviceability in critical moments in buildings of high importance due to post-disaster response or hazardous materials is vital, therefore, the prevention of damages caused by NSCs without any hazard is a demand. Moreover, the repair works interrupt the functionality and operation of the building with significant downtime and costs.

The non-structural components of a building include all building parts and components except those designed as a main member to resist gravity, earthquake, wind, and other types of loads. These components generally specified by architects, mechanical engineers, electrical engineers, and interior designers.

non-structural components usually include but not limited to:

1) architectural features such as interior partitions, exterior cladding, glazing and ceilings
2) Mechanical components such as pipes, ducts, equipment, pumps, generators and unit packages.
3) Electrical elements such as cable tray, lighting, switchgear, and control centre cabinets
4) Plumbing systems such as pipes and equipment.
5) Fire suppression systems
6) Medical gas systems

Earthquake actions for parts and components is addressed in section 8 of AS 1170.4-2007. Based on this section, NSCs have been categorised into two major group, Architectural and mechanical & electrical components, which the later will include plumbing and Fire systems. Except for those exempted by the clause 8.1.4 section, all components need to be seismically designed. Appropriate clearances required to minimise the chance of collision between services and subsequent damages in a seismic event, for both braced and unbraced components, have been recommended in G-172 (Seismic restraint of Engineering Services - Government of South Australia – April 2019) and AS-2785: suspended ceiling design standard. Moreover, NSCs shall accommodate inter-story drift imposed by building during earthquake event.

Based on several factors such as components' characteristics, type of gravity support, spacing between supports, type of base-build structure, accessibility to the primary support and clashes to other services, type and location of seismic bracing should be determined. In addition, efficiency, price of seismic bracing material and labour cost to install seismic bracing on site are important factors in selecting the appropriate seismic restraints type.

One efficient way of addressing the need of NSCs for seismic design and possible bracing is to integrate all the requirements in prefabricated systems. Prefabrication solution can replace the costly and mediocre seismic bracing solutions that are usually installed as a retrofit solution to existing gravity hangers. In this paper, a discussion about the choice of the prefabrication solutions instead of ordinary seismic restraint methods in Australian marketplace will be made.

2 Prefabrication

Prefabricated support is a method of construction that uses components made off-site in a factory, which are then transported and lifted to its location on site. Based on the level of manufacturing and the extent of off-site assembling, there are four main categories of prefabrication in construction based on the level of completeness in the construction process and the component usage.

2.1 Raw Materials

The first category of prefabrication can be termed as "materials". This is the lowest form of raw materials that is manufactured in the factory and are used for construction after being transported to the site. Examples include, 2x4's, floor tiles, brick, CMU, shingles, plywood, etc

2.2 Factory-assembled materials

These require more processing and has a predetermined singular purpose. Examples include precast concrete walls, roof trusses, floor joists, structurally insulated panels, etc.

This refers to pre-manufactured building panels that have structural, plumbing, and electrical, insulation, and enclosure aspects. These include exterior walls, interior walls, and roof or floor panels. These panels are complete and need only to be secured properly once in place.

2.3 Pre-manufactured units/modules

This refers to entire rooms or a specialized part of houses that are built in a factory and are delivered to a construction site and placed using a crane. This practice is common with bathroom and kitchen modules.

2.4 manufactured units/modules

The last form of prefabrication in construction is the entire home constructed in a factory in one or multiple modules and then, delivered to the site. This is most common with modular and manufactured homes. (Syal, M. et all Nov 2020)

In MEP (Mechanical, electrical and plumbing) industry different non-structural components are typically supported by a particular range of supports for gravity purposes. Ceiling tiles are usually supported by cold-formed steel (CFS) frames hanging from soffit or partition walls. Linear mechanical and electrical services such as pipes, ducts and cable trays are typically suspended from steel rods fixed to the soffit. Other individual components such as fans, electrical cabinets and any other elements with considerable weight usually have particular arrangements to support the gravity loads. However, these gravity supports are not checked for any lateral load resistance capacity and the design process typically begins when the components are being installed if not installed already; which is a just in time design approach (Mortazavi, M. et all, AEES 2019)

The common practice for seismic restraint of NSCs is via 3 methods: tension steel wires, cold-formed steel (CFS) struts and less likely CFS prefabricated frames. 2-way wires are used for transverse support only while 4-way wires are used for longitudinal and transverse support. CFS struts can be applied in various arrangements known as rigid assemblies to provide seismic restraint in any particular direction (ISAT REF). In some cases where the first two methods are not practical, the NSC subcontractors are obliged to choose the prefabricated frames which are proven to bring some more advantages with them (Mortazavi, M. et all, AEES 2019)

3 Lateral resistance system

There are multiple type of lateral resistance systems for prefabricated frames. To allow maintenance access under the frames, transverse frames are typically moment-resisting frames that support gravity loads and resist lateral loads transverse to the frame. See Figure 1 for a typical transverse frame. Although the frame is shown with fixed base columns, it can also be constructed with pinned base columns if the supported piping can tolerate the lateral displacement. The transverse frames are typically connected with longitudinal struts. If diagonal bracing is added in the vertical plane, then the struts and bracing act together as concentrically braced frames to resist lateral loads longitudinal to the frame. See Figure 2 for an isometric view of a typical frame. If the transverse frames are not connected with longitudinal struts, the prefabricated frame is considered to be "un-strutted." The frame columns act as cantilevers to resist lateral loads longitudinal to the frame. (Richard, steel pipe rack, 2010)

The transverse frames are usually moment-resisting frame systems, and the choices are special steel moment frame, intermediate steel moment frame and ordinary steel moment frame. In the longitudinal direction, if braced frames are present, the choices are usually special steel concentrically braced frame and ordinary concentrically braced frame, although there is nothing to preclude choosing steel eccentrically braced frames or buckling-restrained braced frames. If braced frames are not present, the choices in the longitudinal direction are one of the cantilevered column systems. In both directions, the seismic system selected must be permitted for the prefabricated frames' height.

Figure 1- Prefabricated racks

Figure 2- Prefabricated Mechanical Risers

4 Design Loads

Imposed load to the prefabricated frames applied based on operation loads. Design loads are summarised here: (Drake, R. et all, 2010)

4.1 *Dead Loads*

Dead loads are defined as the weight of material of construction including, but not limited to structural items, and the weight of fixed service equipment, such as cranes, plumbing stacks and risers, electrical feeders etc. Prefabricated frames and their foundations should be designed to support these loads applied on all available rack space unless other criteria are provided by the client.

4.1.1 *Structure dead load*

The weight of materials forming the structure, and all permanently attached appurtenances. This includes the weight of fire protection material, but does not include the weight of piping, cable trays, process equipment and vessels.

4.1.2 *Operating dead load*

The operating dead load is the weight of piping, piping insulation, cable tray, process equipment and vessels plus their contents (fluid load). The piping ducts and cable tray loads may be based on actual loads or approximated by using uniform loads. Other uniform loads may be used based on client requirements and engineering judgment. For cable tray levels, a uniform distributed load.

4.1.3 *Empty dead load*

The empty weight of piping, piping insulation, ducts, cable tray, process equipment and vessels. When using approximate uniform loads, 60% of the operating dead load for piping levels is typically used.

4.1.4 *Test dead load*

The empty weight of the pipes plus the weight of the test medium

The use of large approximate uniform loads may be conservative for the sizing of members and connections. However, conservatively large uniform loads can become unconservative for uplift, overturning and period determination.

4.2 Live Loads

Live loads are defined as “Those loads produced by the use and occupancy of the frame, and do not include construction or environmental loads such as wind load, snow load, rain load, earthquake load or dead load.” Also, it necessary to apply stairs and platforms live loads on the frame. Often, the live load design criteria are specified by the client and may be larger to accommodate additional loads for maintenance.

4.3 Thermal Loads

Thermal loads are defined as “Self-straining forces arising from contraction or expansion resulting from temperature change.” Thermal loads may be caused by changes in ambient temperature or may be caused by the design (operating) temperature of the pipe. Specific thermal loads for prefabricated frames cab be prescribed such as below:

- Thermal forces
- Pipe anchor and guide forces
- Pipe friction forces

Ambient thermal loads are typically neglected for prefabricated frames because they are often insignificant to other loads. However, there may be cases where they should be considered, such as project sites in locations with extreme temperature ranges. If thermal loads are considered for long prefabricated frames, structure expansion joints should be placed for the components. These expansion joints could be provided by either omitting the struts at one bay or by using long-slotted holes in the strut-to-column connections in the bay. If expansion joints are provided, each frame section between joints should have at least one bay of horizontal and vertical bracing near the centre of the section.

4.4 Earthquake Loads

Earthquake loads are prescribed of earthquake loads and motions form the below conditions:

- Consider an operating earthquake load. This is the load considering the operating dead load as part of the seismic effective weight.
- Consider an empty earthquake load. This is the load considering the empty dead load as part of the seismic effective weight.

4.5 Wind Loads

Wind loads are determined in accordance with the following conditions:

- Calculate wind on the prefabricated frame, neglecting any shielding.
- Calculate transverse wind on each pipe level. The tributary height for each pipe level should be taken as the pipe diameter (including insulation) plus 10% of the prefabricated frames transverse width. The tributary area is the tributary height times the tributary length of the pipes.

4.6 Snow Loads

Typically, prefabricated frames are much different than building roofs, and the flat areas of a prefabricated frames where snow can accumulate vary. Thus, engineering judgment must be used when applying snow loads. The flat-roof snow load could be used for determining the snow load on a prefabricated frame. The area to apply the snow load depends on what is in the prefabricated frames and how close the items are to each other. For example, if the prefabricated frames contain cable trays with covers, the area could be based on the solidity in the plan view. If the prefabricated frames only contain pipe with large spacing, the area would be small because only small amounts of snow will accumulate on pipe. By using this approach, combinations with snow load usually do not govern the design except in areas of heavy snow loading.

4.7 Relative seismic displacement

Components connected to the building structure at more than one level require to be able to sustain the relative seismic displacement between the level. the displacement needs to be determined from the building's calculated design displacement, where it is known. If the displacement is not provided by the designer, the maximum displacement between floors can be calculated as 0.025 time the story height. For some components such as pipes in risers, relative seismic displacement between support points is usually more significant than seismic forces due to acceleration.

5 Restraint type selection

The first stage of the design is restraint type selection. This choice depends on various factors such as cost (material, design, installation), time limitations, access to the component to be installed (being already assembled or not), location of component within the floor level (floor mounted, hanging from soffit or any other arrangement), and weight of the component.

5.1. Clashes and allowance for seismic clearance

One major complication with design of seismic restraints for a building with various HVAC systems and NSCs is positioning the seismic restraints. As previously discussed, one individual subcontractor looks after each set of NSCs shown in Table. This indicates the necessity of close coordination between different subcontractors and the seismic engineer. And the situation can become even more complicated when each subcontractor approaches a different seismic engineer or consulting company. Considering parallel seismic design procedure for each component, one can imagine the level of complication involved with clashes of seismic restraints for different components. Not only clashes, but also a minimum seismic gap needs to be allowed for, between components and their corresponding restraints [6].

5.2. Inspections and certification

For a seismic engineer to be able to issue the seismic restraint installation certificate, access should be provided for visual inspection of every individual restraint and its anchorage to main structure. The other practice is assigning a code number to each restraint and take a picture of each restraint to be sent to seismic engineer with the code attached to picture. This method facilitates the inspection both for seismic engineer and subcontractor.

5.3. Prefabricated supports designed for gravity and seismic loads

Typically, all NSCs are separately assembled and installed on site by installers from different subcontractors. This leads to higher costs, construction time and level of complication. This approach eliminates majority of coordination complications and consequently, reduces the increased cost and time of design and installation.

One step further in advancing the process, is having as many NSCs as possible installed to the same prefabricated support. By early coordination of mechanical and structural engineers, all NSCs are located within a prefabricated frame system. This allows the seismic engineer to consider all involved component weights and locations to analyse and design the prefabricated support. Each of the supports carrying various components are referred to as one module. After being analysed and designed, the modules can be assembled off site and delivered to the job site. This approach is even more efficient than the previous one since the seismic analysis and design process is conducted once for a number of components. This eliminates the access issues or any risk of clashes and reduces the onsite work resulting to enhanced quality control.

5.4. Demographics considerations

Demographic forces relate to people: prefabrication removes people from construction sites and brings them into the controlled space of a manufacturing environment. This regulated workplace works with existing access to factory environment, generally away from populated areas, with permanent amenities, enabled work activities with increased safety and enhanced supervision and quality control. This results in highly improved quality of work, worker safety and opportunity for skill acquisition and integrated learning.

5.5. Ecological considerations

Prefabrication creates modules of complex systems but limits waste and eliminates the need for additional restraints. Modules are pre-assembled offsite in required order and transported to be attached to structure. This results in major reductions to site works in lay down areas, number of construction personnel, tools required, required storage of parts and components and waste.

Taking all the decision criteria into account, the seismic engineer can propose the proper seismic solution to the subcontractors. (Mortazavi, M. et all, AEES 2019)

6 Advantages and disadvantages

6.1. Advantages:

6.1.1. Cost-effectiveness:

It also costs less to transport partial assemblies from a factory than to move pre-production resources to each site. It is possible to place prefabrication sites where skilled labour is more readily accessible and the costs of labour, electricity, materials, space, and overhead are reduced.

6.1.2. Time savings:

Building time is thereby decreased, resulting in lower labour costs. Reduction in construction time to allow an earlier return of the invested principal.

6.1.3. Quality control:

Construction guarantees precise compliance with building codes and excellent quality assurance. Along with quality control and factory sealing, high-energy performance.

6.1.4. Lower environmental impact:

Reduced the quantity of waste materials relative to building on site

6.1.5. Better safety and security:

By reducing a construction site’s timeframe, you simultaneously decrease the amount of time that the site is vulnerable to vandalism or robbery.

6.1.6. Flexibility:

This greatly decreases the demand for raw materials, minimises the resources spent and overall reduces time.

6.1.7. Reduced Site Disruption:

There is much fewer truck traffic, machinery, and material suppliers around the final construction site as several parts of a support are completed in the factory.

6.2. Disadvantages:

Some of the challenges of prefab construction can be described as below:

6.2.1. Regulatory code officials, inspectors

Modular building design and construction requires high levels of cooperation between project parties, particularly architects, MEP engineers and manufacturers.

6.2.2. Design restrictive / aesthetics limitations

Also, the initial preparation of designs is time-consuming. The connections are to be designed and constructed with high regards to details to accommodate the relevant load. The strength and solidity of the whole MEP services rely upon the strength of the connections. Therefore, rather than component-based analysis, it is important to have detailed studies on the whole system.

6.2.3. Transportation logistics

For the larger prefabricated assemblies parts, transportation costs can be high. The available crane capacity at both site and fabrication locations can also contribute to limitations in modular construction. The allowable width and height of the module can be constrained due to limitation of the transportation carrier (barge or truck). If access to the site is water then the module can be limited by barge/vessel allowable shipping weight limits. Large prefabricated parts require heavy-duty cranes and measurement of precision from end-to-end management.

6.2.4. Designer's knowledge of modular

Efforts should be made to keep the interfaces between modules as simple as possible with provision for installation tolerances. It is recommended to make adjacent structural modules structurally independent instead of obtaining a fit between the two modules at site.

6.2.5. Early engagement of modular manufacturer

Early engagement with engineering workshops and suppliers may be necessary to ensure that procurement of equipment is done in a timely manner to allow modularization execution to be carried out without minimum hindrance.

7 Conclusion

Adding seismic restraints to existing gravity support is a traditional approach that can be enhanced by using prefabrication solution. Prefabrication can integrate all requirements of NSCs components including seismic requirements and while minimising the overall cost of the projects when considering time constraint and quality control required. Not only the analysis and design process for gravity and seismic loads are unified in prefabrication solution, but also the time and cost, installation and inspection of supports can be more effectively under control. More safety and security combined with flexibility are achievable and minimises the resources and deliverable items would be resulted. Seismic restraint design and construction requires high levels of cooperation between project parties, particularly architects, MEP engineers and manufacturers, which in prefabrication method this can be achieved with less hassle. In conclusion, it is author's suggestion that prefabrication solutions can be adopted more frequently in building services sector to improve schedule, quality and also to decrease costs in projects across Australia.

8 References

Syal, M. and Bakliwal, H. (2020). Overview of Prefabrication in Residential Construction, Housing Education and Research Initiative Construction Management Program School of Planning, Design and Construction Michigan State University October 2020.

Gunawardena, T (2016). Behaviour of Prefabricated Modular Buildings Subjected to Lateral Loads, Department of Infrastructure Engineering The University of Melbourne October 2016

Mortazavi, M. and Nazari Rad, A and Fooks, J. and Bartlett, J. Seismic restraints for non-structural components in Australian marketplace: prefabricated solutions, Australian Earthquake Engineering Society 2019 Conference, Nov 29 – Dec 1.

Drake, R. and Walter, R. Design of Structural Steel Pipe Racks, Engineering Journal/ Fourth quarter 2010, p 241-252

AS 1170.4: 2007. Structural Design Actions, Part 4, Earthquake action in Australia

Vin Civilworld, Updates in civil engineering, architecture finishes, building construction, Environmental Engineering, Prefabrication: All Advantages & Disadvantages Explained, March 2021