

Identification of Structural Issues in Design and Construction of Multi-Story Modular Buildings

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ABSTRACT

As the modular construction industry tries to find new markets in multi-story buildings, additional challenges are faced along the way that needs to be addressed. This paper initially introduces different types of modular multi-story or high-rise construction systems. The structural systems including gravity and lateral load resisting systems are then discussed. The challenges that structural designers face in addressing load path continuity and gravity and lateral load transfer between adjacent structural components are reviewed. Approaches for system and building modeling needed for structural analysis as well as relevant building code requirements are discussed. Furthermore the challenges in design and detailing of different structural members and components/systems are evaluated. The paper also provides an overview of any special structural safety issues for design and construction. Finally, the paper outlines the R&D needs for advancing the technology of multi-story modular building design and construction.

INTRODUCTION

Modular construction is known for its economic advantages and high construction quality of the modules because of the factory construction environment. Despite the simplicity of the construction of modular single-family dwellings that brings about speedy erection at the job site, the same thing cannot be stated for multi-story modular buildings. With increase in the number of stories, the construction method and structural engineering issues become more complicated, in particular when lateral loads also need to be considered. There is lack of good or sufficient understanding of the structural behavior of such multi-story construction. Nonetheless, interest exists in multi-story low-rise, mid-rise and high-rise modular construction, in particular in urban and metropolitan areas. However, because this technology is relatively new with limited understanding of structural performance under extreme loading conditions, most applications of multi-story modular construction are currently in low-rise buildings or in areas with minor natural hazard potential. However, construction of multi-story modular buildings in the United Kingdom has shown significant progress in developing and advancing this construction technology.

By improvement of technology, the methods of construction can be changed. As shown by the popularity of the use of panelized components in commercial and industrial construction, there are various benefits in shifting from all site construction to more

panelized and modular construction of residential buildings. Lawson and Ogden (2008) mention the following three major benefits of the modular construction of buildings:

(a) Lower construction cost—as the number of plant fabrication increases, the constant cost of the plant will be shared by more fabrication, thus reducing the total cost; (b) Shorter construction time—because of reduced jobsite activities; (c) Higher quality production—because of better plant fabrication and inspection.

In recent years, numerous mid-rise and high-rise modular buildings have been built around the world (MBI, 2011). Due to lack of specific code or standard for construction of multi-story modular buildings, different innovative structural systems are used in these buildings, and general building code requirements are normally considered for safety-related issues; for example in United States, most of the multi-story building are designed according to International Building Code (IBC, 2012). As for each new innovative system, multi-story modular buildings with their own characteristics pose unique challenges for prediction of their behaviors under structural loads; there is very limited research available on different types of such systems. In particular, there are no specific design criteria for this type of structural system. In addition, due to the complex nature of structural components and connections of modular buildings, structural modeling and analysis are more complicated in comparison with conventional (non-modular) buildings. In this paper, for each multi-story modular system type, some important structural aspects are discussed that needs consideration for structural design and modeling purposes.

IDENTIFICATION OF DIFFERENT STRUCTURAL TYPE OF MULTI-STORY MODULAR BUILDING (MSMB)

By considering structural aspect of these buildings, we can categorize them in the following six major groups: 2D, 3D, Open Building System, Hybrid Cored-Modular, Hybrid Podium, and Framed Unit systems.

2D systems

In 2D systems, prefabricated floors and walls are installed and assembled to create a whole building. First, columns and walls of each story are installed, followed by installation of floor cassettes on these columns and walls (Lawson et al., 1999). A good example for this system is a 30-story hotel in China near Dongting Lake where it was erected in just 15 days. As depicted in Figure 1, the structure has two main components, which are roof/floor cassettes and columns (Jackson, 2012).

Floor diaphragm system is strongly related to the type of modular building. Generally, in 2D



Figure 1. Dongting Lake Hotel with 2D structural system using floor cassette-column-connection example (Jackson, 2012)

systems and Open Building systems, panelized floors (e.g., floor cassettes) are supported by walls or a framed structure (as shown in Figure 1) requiring constraining of floor joints in these systems. The main function of connections between 2D panels is integration of panels and load transfer between them. Connections must have adequate strength to transfer gravity and lateral load between panels. An example of connections in 2D system is also depicted in Figure 1 (Jackson, 2012). As shown in this figure, these connections consist of rigid bolt fasteners. In addition, a shear key is considered at the top of the column, which goes to the floor cassette and gives rise to uniform movements of the joints at floor level. Furthermore, due to the use of wings for the column, a rigid connection is achieved between the column and the cassette. The behavior of this structural system under lateral loads, resulting from wind loads or earthquake induced drift, will depend on whether such resistance is relied on stair tower walls or elevator shafts, or whether some bays employ certain bracing system. In general, in such construction, emulation of conventional rigid frame behavior in analytical modeling may not be the most appropriate approach, and innovative systems may need to be employed. In particular, for use in high seismic regions, appropriate energy dissipating systems need to be developed.

3D Systems

In this modular system, the structure consists of many 3D modules, which are stacked vertically and attached horizontally to create the 3D building. Each module can be part of a unit, one complete unit, or even more than one unit. The size of the modules is related to the location of the module in the building, construction equipment and transportation limits. Usually modules in this system are in the range of 100 to 600 square feet (Lawson et al., 2010). Based on the study of load paths for this type of structure, 3D system can be divided into two main subcategories, which are “Wall-Load Bearing” and “Corner-Supported” systems (Lawson et al., 2010).

Wall-Load Bearing systems

In wall-load bearing systems, gravity loads (live and dead) are transferred to the walls, which will then transfer loads to the foundation. Load bearing elements of these modules are walls and usually consist of many repetitive C section (light gage steel studs) profiles along the wall. Lateral loads within the module are resisted by bracing elements and/or sheathing. Another structural system that is common for these walls is steel sandwich panel. The spacing of these profiles or the strength of panels depends on the amount of gravity loads, location of the module, and lateral load magnitude. In Figure 2, a module with load bearing walls is depicted (Lawson et al., 2005b).



Figure 2. Wall-Load Bearing module with steel C-section profiles (Lawson et al., 2005b)

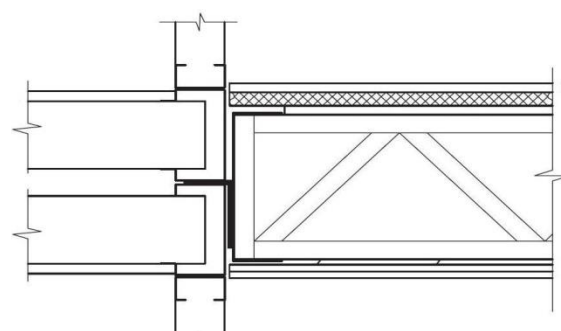


Figure 3. An example of entire building floor diaphragm in stacked modular construction (Lawson et al., 2008)



Figure 4. Individual module diaphragm of a module (Lawson et al., 2008)

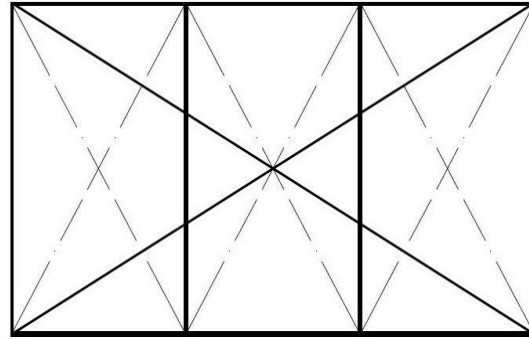


Figure 5. Difference between entire building diaphragm (continuous lines) and individual module diaphragm (dashed lines)

Generally, in 3D systems and their combinations, the floor of the building consists of many discrete floor elements (unit diaphragms). Therefore, the integrity of these discrete units, which is provided by the diaphragm, is very important in these systems. There are two diaphragm systems that need to be differentiated. The entire building floor diaphragm is a structural system that distributes lateral story loads to lateral load bearing elements of the structure; an example of this diaphragm is presented in Figure 3. The building floor diaphragm helps floor joints to have uniform lateral movement. This diaphragm constrains top joints of the lower modules and bottom joints of upper modules by tying them together at each story for horizontal movement of the floor. This diaphragm also helps bring about integrity of the modules and ensure uniform lateral movements of modules in each story. It also functions to distribute horizontal floor loads to vertical lateral load resisting structural elements. In 3D systems and their combination with cluster and podium systems, floor panels of the stacked modules and the connections between modules cannot sufficiently constrain floor joints together; therefore additional diaphragm system would be required. Figure 4 shows an example diaphragm system for 3D modules (Lawson et al., 2008).

In addition to the entire building floor diaphragm, each module should have its own individual module diaphragm. The module diaphragm constrains the joints of a module together in the floor plane at the top as well as the bottom of the module. As shown in Figure 4, the module diaphragm can consist of a crossed cable diaphragm bracing, which constrains opposite corners of the module together (Lawson et al., 2005a). In addition, the difference between module diaphragm and building floor diaphragm is shown in Figure 5.

Module diaphragms in these systems perform different functions during construction and after the construction. During the construction phase, this diaphragm helps increase rigidity and stability of the module, especially at the time of erection and installation when it enhances twisting and buckling resistance of the module. After completion of the building construction, the module diaphragm forms a part of the building diaphragm to distribute loads among structural elements, especially under lateral loads.

Corner-Supported systems

In this system, the corners of the modules support the gravity loads, which are transferred by edge beams of the modules. The columns and edge beams (normally deeper than those in wall-bearing modules) in this system carry gravity loads, while some bracing elements or



Figure 6. Corner-Supported module (Lawson et al., 2005b)

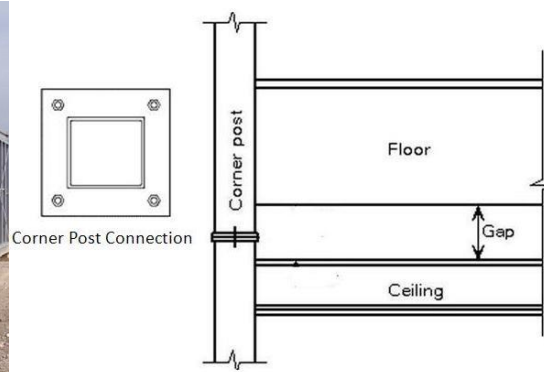


Figure 7. An example for connection of two stacked 3D models (SteelConstruction.info website)

sheathings resist the lateral loads. Steel Hollow Sections (SHS) are the most common profile types for use as the corner column sections. One example of a corner supported module is shown in Figure 6 (Lawson et al., 2005b). A critical performance aspect in such system would be the lateral load response of the building made up of stacked modules. Depending on the relative stiffness of the floor and ceiling beam and their connections to the corner posts, the behavior of the post at post-to-post connection can be different. In any case, such behavior will also be dependent on the type of entire building lateral load resisting system. In Figure 7, an example of connections between two stacked corner-supported 3D modules is illustrated.

The Open Building System

The Open Building system is developed to enhance the flexibility of space planning and may consist of various combinations of framing and module systems as appropriate. In one type of such systems, two integrated framing systems transfer both gravity and lateral loads to the foundation. The interior structure of the module is one of these frames. The second frame is the exterior frame, which consist of columns on exterior edge of the structure (or some in the middle rows) at a constant spacing. The procedure of the construction of the Openhouse system (one type of the Open Building system) has three main steps. First, the job-site fabricated columns are erected. In the second stage, the modules are installed between the columns of the first stage; as depicted in Figure 8, the columns are positioned in the hollow spaces within the modules. In the last stage, by installation of a uniform roof system, all of the module elements and the columns of the first stage will be integrated together for the lateral movements. In Figure 8, two photos from different stages of construction are shown (Bengt Birgersson, 2004).

Figure 8. Two photos from two different stages of construction of an Openhouse building (Bengt Birgersson, 2004)



As in conventional building structures, roof and floors behave as diaphragms of the structure at each floor level, and these diaphragms integrate interior and exterior frames for gravity and lateral loads resistance.

When a multi-bay structure is loaded in the lateral direction, the columns or walls in adjacent bays tend to slip with respect to one another if not tied together properly. In conventional building construction, the connections of horizontal and vertical elements are designed for combination of gravity and lateral loads. Therefore, the continuity of load path between horizontal and vertical elements exists and the integrity of the system is provided. However, due to discontinuity between modules in modular building construction, the modules must be connected to one another in the vertical direction to resist vertical shear forces (caused by lateral loads) between modules. In Open Building systems, the columns that are installed at the first step should be structurally connected in the vertical plane to the adjacent modules. Figure 9 shows the difference in deflection modes between the two systems when the adjacent vertical load carrying systems are not tied to one another and when they are tied. In the figure on the left, there is no vertical deformation coupling between adjacent components, while the figure on the right shows the vertical shear transfer between such components.

Hybrid Cored-Modular Systems (Cluster)

As the height of a structure increases, the magnitude of the total lateral and gravity loads increase and therefore, the size of load-bearing elements in lower modules will have to be larger beyond what is needed just for gravity loads. In cluster systems the size of these elements are limited by considering a core for the structure.

Generally, due to erection and installation issues, prefabricated modules should be kept light (e.g., by using light gage steel) and as a result they have lower lateral stiffness in comparison with regular (e.g., rolled steel) framings. However, conventional concrete shear walls and frames, braced steel frame, and steel moment frames have higher lateral stiffness in comparison with prefabricated modules. By installation of one or more of these stiff systems between modules as the core, lateral deformations of the whole structure can be reduced. Under lateral loads, the diaphragms at the floor levels will transfer most of the lateral loads to the stiffer (core) parts of the structure. Therefore, the connection between the core structure and the modules should be strong enough to transfer tension-compression and vertical loads between these two structures. As depicted in Figure 10, the stacked modules rely on a braced steel frame to resist lateral deformations. In Figure 11, the

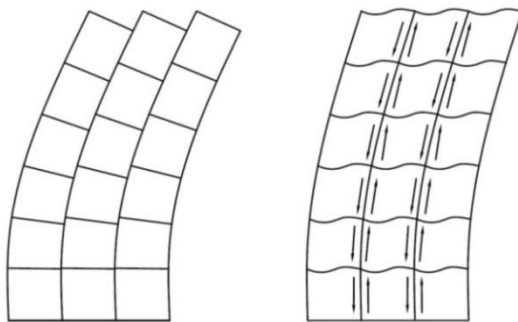


Figure 9. Vertical Shear transfer between stacked units: (left side) No vertical shear transfer; (right side) Coupled at vertical joints

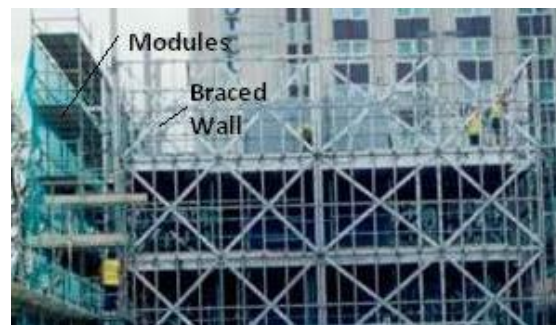
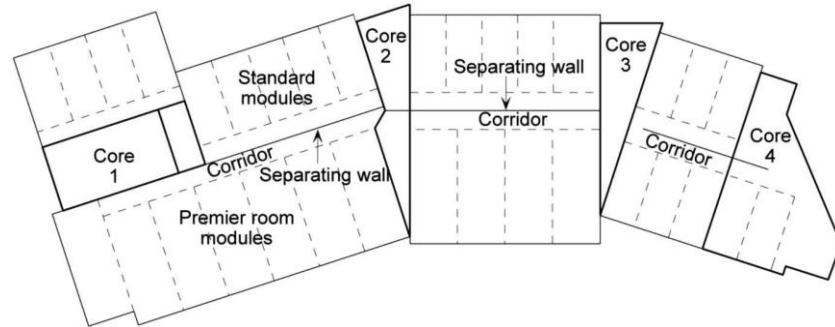


Figure 10. Stacked modules, supported by steel frame (Lawson et al., 2005)

Figure 11. Arrangement of cores in the plan of a 12-story building (Lawson et al., 2010)



plan of an 11-story modular building is depicted. This is a student residential building in Bristol. As shown in this Figure, there are 4 steel braced cores in the plan that resist lateral loads applied on the structure (Lawson et al., 2012).

Hybrid Podium-Modular Systems

One of the limitations of modular buildings is short bay spans for lower stories normally desired for retail or parking space. The hybrid podium-modular system is normally used in structures that need longer bay spans in lower stories. In podium-modular systems, some of the bottom stories (usually two stories) are built using conventional structural steel or concrete frames with long spans. Then, the modular part of the building would be installed on top of the podium. In other words, the podium is like a foundation for the modular parts. The modules transfer their uniform load to the beams of the podium. In addition, a podium structure with long spans behaves as a soft story for the structure leading to an increase of the period of the structure, which results in a decrease of design earthquake forces.

A schematic drawing of a 2-story podium system is shown in Figure 12 (Lawson et al., 2010). As shown in this figure, the edges of the modules are aligned to the center of the podium beams to omit eccentricity of the loading on podium beams and columns. In conventional structural models, one usually assumes that all elements at a given floor level are located in a single plane, which is the diaphragm level. But, as depicted in Figure 7, in some types of

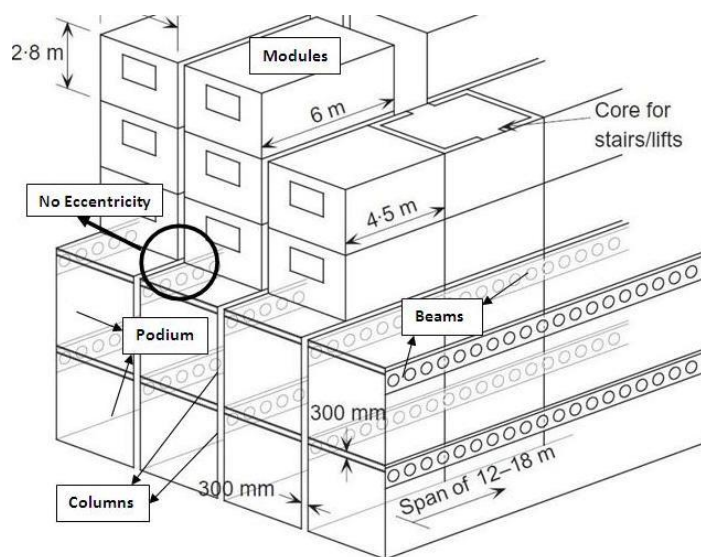


Figure 12. A 2-Story podium beneath a multi-story modular building (Lawson et al., 2010)

modular buildings such as 3D systems, the bottom of the upper modules do not lie in the same plane as the top of the lower modules; they are just linked together at some points. In other words, there is an elevation difference between the ceiling of a story and floor of the next story; and this should be addressed in the model. This difference is more distinguished when the designer wants to model the interface of the podium and the modules. Therefore, the designer must consider two

different closely spaced planes for floor and ceiling to link upper and lower joints of these elements at sufficient number of points to ensure continuity and integrity of these separate modules. An example of the finite element model to represent the diaphragm in such systems is depicted in Figure 13.

Framed Unit Systems

In this system, the main structure of the building is not constructed as modular. As depicted in Figure 14, the main structure of this type of construction is a conventional structural frame. After erection of the main structural frame, prefabricated units will be placed and fitted between beams and columns of the structural frame. Figure 14 shows the Contemporary Resort Hotel of Disneyland, built in 1971 (Walt Disney Drawing Board website). The main structural frame is a braced steel frame. The modular units of this structure are made of wood and cannot therefore bear large deformations as much as steel frames do. This is one reason for the use of braced frame, which increase the stiffness of the structure and control the deformation of the frame under lateral loads.

One of the most important benefits of this system is that the properties of module elements are not dependent on the plan shape, number of stories, and wind and earthquake loads, and due to the fact that the main structural frame bears the loads, all of the units can be identical. In addition, the elements of the modules are designed just to carry their own gravity loads and construction loads; therefore, the weight of the modules is lower than the weight of the other types of the 3D modules. In spite of the fact that the main structural frame carries the lateral loads, the connection between the modules and the frame should be strong enough to be able to transfer the gravity loads and the earthquake loads, which result from the acceleration of the mass of the modules. In modeling such a system, a suitable diaphragm should also be considered in order to properly model the integration of the modules and structural frame. In addition, to avoid unbalanced loading of the structural frame during construction, a detailed and exact construction procedure should be presented by the design groups to avoid failure of the structure at the time of the modules installation.

ISSUES COMMON TO MOST TYPES OF MULTI-STORY MODULAR SYSTEMS

In addition to specific challenging issues related to each structural system of multi-story modular buildings, there are some common issues that should also be addressed in all

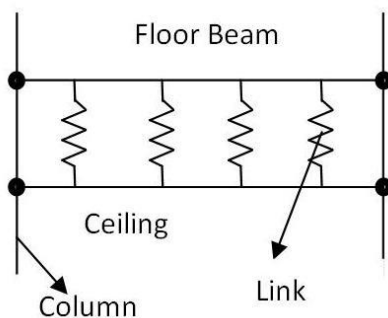


Figure 13. An example of floor finite element model for module



Figure 14. Contemporary Resort Hotel in Disney land (1971)

different types of these modular structures. In code-based design of structures to resist earthquake loads, one needs to determine the response modification factor (R) value. As for any new structural system type, it is a challenge to determine a reasonable R factor value, and as a result, without extensive analytical studies or experimental testing, specific value for R factor cannot be obtained. Further challenging in the determination of R value is the fact that due to the difference in lateral resisting systems, R factor would have different values for different types of modular buildings. In nonlinear design of conventional construction, plastic hinges that form in members near the connections help dissipate the seismic energy. In modular construction however such plastic hinging in members is not expected to occur because of the existence of various flexible joints in the system. Therefore, the designer should think of alternative approaches to develop appropriate systems or components that will dissipate energy.

Detailed finite element modeling of entire modular buildings is complicated because of the variety of joint and support types with unknown load-deformation properties. For practical application of finite element modeling of modular systems some simplifying modeling assumptions are necessary. For example, a two-tier modeling approach will be one option where for tier one, each module can be simplified and assumed as a 3D sub-frame as shown in Figure 15 to represent the modules shown in Figure 6 and 7. K_c , K_{bf} , K_{bc} , and K_j represent, respectively, the stiffness of vertical members, floor level horizontal elements, floor level horizontal elements, and joints. Once the entire building is modeled using 3D sub-frames, the structure can be subjected to applicable loads and analyzed. The forces the sub-frame experiences can then be used for a more detailed second tier modeling. Using the forces resulting from the analysis of the entire building model (first tier modeling) and applying them in a second tier more detailed finite element model of each module, we can then design internal elements of the modules such as beam, columns, ceiling beam, floor beam, bracing or shear walls, etc.

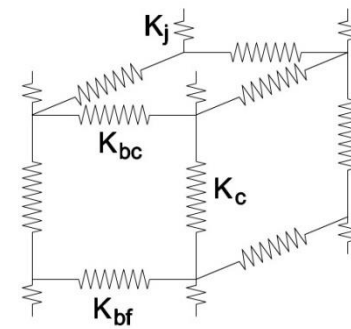


Figure 15. A 3D Finite model for a 3D module

Safety and robustness of the structures are important factors that designers must take into account in the design of the structures (Lawson et al, 2008). There may be many situations that could bring about the failure of some modules. Some of these situations are faults in the factory where modules are assembled, damages during erection or transportation, failure due to fire or explosion, terrorist attack, and plain collision. Therefore, elements and connections must have enough redundancy to prevent repetitive failure or progressive collapse of the structure, when some of the modules fail. Accordingly, the modules must have a reliable integrity and the continuity needed to be able to bear the loads transferred from failed modules. Furthermore, contractors cannot prevent all of the installation problems and eccentricities during the sequence of module installation, and therefore, the designer must consider installation problems and provide allowance in their design calculations and drawings. Some internal forces must be added to the module elements or alternatively the factors of safety increased.

SUMMARY AND CONCLUSION

As for any relatively new system, unknown structural behavior and lack of sufficient specific design and construction guidelines and code requirements are two main reasons that designers or contractors may not be inclined toward selecting modular construction building. In order to make multi-story modular building more popular and reliable system, challenging issues for the structural aspects have to be carefully addressed.

In developing computer modeling, the following issues should be considered: load definition, modeling of modules overlap, element definition, and identifying loads during construction. Furthermore, there are some important challenges in structural design of the building, including the following: Individual module horizontal diaphragms, whole building floor diaphragm, continuity in vertical plane, and connection of units. The importance degree of the above mentioned challenges can vary based on job site condition and natural disasters in the region to be considered in design; for example in places that are not exposed to storm and earthquake load, the importance factor of some elements such as diaphragms and vertical connections reduces. Finally, it should be mentioned that studying existing modular building systems, evaluation of their performance, and discussing pros and cons of each system can effectively be helpful to address the above mentioned challenges.

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