Characterization and Monitoring of Seismic Performance of Post-Tensioned Steel Modular Structures

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SUMMARY:
Modular structure systems are increasingly used in the building construction due to their advantages in terms of manufacturing quality, speedy erection on-site, efficient use of materials, lower life-cycle cost, as well as some other environment-friendly features. This paper presents a study on the characteristics of the seismic behaviour of a post-tensioned modular system (PTMS), made of tubular steel frames. A simplified model with beam-column and link elements is developed for the analysis of the global response of the structure and interactions between the pre-stressing system and main frame components under seismic loading. For the complex nonlinear behaviour of local regions, a refined FE model is employed. Three potential failure modes are identified. The seismic capacity of a typical multi-storey modular building is evaluated and possible enhancements are discussed. In addition, a low-cost structural health monitoring system for the particular structural condition and performance monitoring is described.

Keywords: Modular structure, tubular frame, post-tensioning system, seismic response, structural monitoring

1. INTRODUCTION

Lightweight steel structures are increasingly used in modern building construction (e.g. Pedrazzi and Lozano, 1998; Popovic, 1998). Apart from pre-fabricated structural components such as curtain walls, ceilings and floors, self-contained modular units are also being developed. Building systems constructed by assembling modular units are sometimes called open house systems (Veljkovic and Johansson, 2006), volumetric structures (Powerwall, 2008), or modular steel buildings (Annan et al., 2009). The general advantages of module systems include higher accuracy and efficiency of production, shorter construction period, reduced use of skilled labour for on-site work, lower life-cycle cost, less construction waste, and thus generally improved sustainability.

In this study, a novel modular system, referred to herein as post-tensioned modular system (PTMS), is considered. Full details of the system can be found in (Powerwall, 2008). Structurally the system is formed by assembling modular frame units through connectors at the floor levels and tie (tension) rods. The pre-stressing achieved via the tensioning rods effectively keeps the whole system tight, and in conjunction with the connectors it also provides a mechanism for lateral load resistance. Such type of systems has distinctive structural features due to the pre-stressing mechanism, and hence requires specific modelling considerations.

2. STRUCTURAL CHARACTERISTICS OF PTMS

As indicated in Fig. 1, the PTMS is an assembly of a number of modular frames integrated by tie rods. Each modular unit is a basic rectangular frame made by steel tubular members. The modular frame units are stacked on top of (and next to) each other, usually via a connector at each joint. Tie rods are passed vertically through the tubular columns, and attached to the connector via a lock nut as each storey is erected. Final tightening (post-tensioning) is applied at the top when the whole structure is erected. The relative movement between the modular units in the transverse direction is resisted by friction or gripping, in conjunction with the shear resistance provided via the connectors. Fig. 2 schematically illustrates the force paths in a post-tensioned modular system.

Figure 1. Building structure made from modular units and tie rods (courtesy Powerwall, 2008)

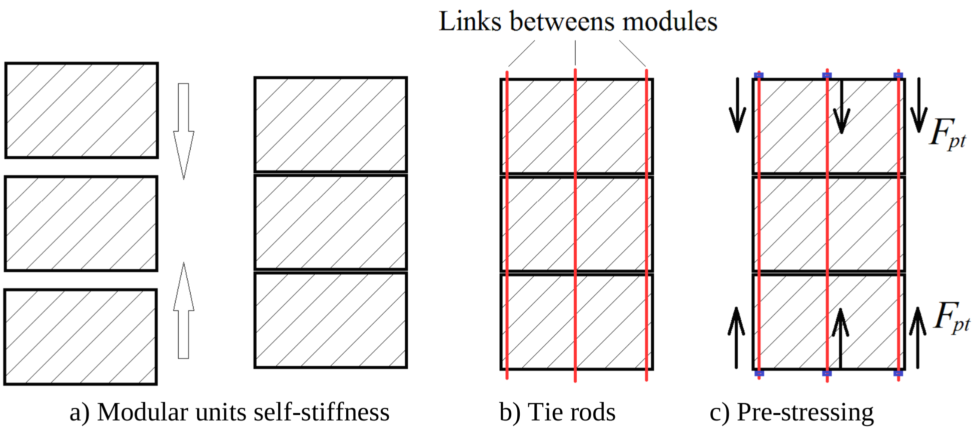


Figure 2. Schematic of a typical PTMS

When subjected to lateral (wind or seismic) loads, the load resistance mechanisms in a PTMS will exhibit the following features:

1) Re-distribution of stress and associated nonlinearity: As lateral load are applied, re-distribution of stresses occur between the tensioning rods and the modular frame members. Vertical separation (uplifting) in the vertical direction could occur when the pre-stress in the frame columns is overtaken by the effect due to the lateral load-induced overturning moment. This marks a critical situation concerning the overall integrity and rigidity of the entire system. A separation between modular units will lead to a step reduction in the global stiffness because the contribution of the affected modular columns to the axial stiffness reduces to zero. Consecutive separations will manifest in the load vs. (vertical) deformation response with a piece-wise linear behaviour (without involving material nonlinearity).

2) Interaction between modular frames and tension rods: tension rods may be attached to the modular frames directly or via the connectors by lock-nuts at the floor levels. The presence of lock nuts provides redundancy allowing for staged re-distribution of the axial force when separation (uplifting) occurs.

3) Potential failure modes: three distinctive failure modes can be identified in a PTMS when it is subjected to lateral loading: a) failure of tubular components within a modular frame, with buckling of a tubular column or bending failure in columns/beams; b) failure of tension rods (e.g. loss of effective locking); c) connection failure at the modular joints, normally with local failure in the tubular columns

around the connectors.

3. SIMPLIFIED FE MODELLING METHODOLOGY

3.1. Basic modelling considerations

Due to the complexity in the contact behaviour between the modular frames and the tensioning rods, a detailed analysis involving detailed contact simulation can be computationally demanding. Herein a simplified method is proposed.

1) Tie rods and post-tensioning force: The tie rods in a PTMS are modelled using bar elements (tension only). The post-tensioning force is established by setting an initial tensile strain in the bar elements. Consider a PTMS with tensioning rods being fixed at the top and bottom ends. Let the pre-tension force to be installed in the rod be F_{pt}, the axial rigidity of the tie rods and the tubular column be $E_t A_t$ and $E_m A_m$, respectively, and the total length (height) of the PTMS be L, the required initial strain can be calculated as follows:

$$d_t = \frac{F_{pt} L}{E_t A_t},\ d_m = \frac{F_{pt} L}{E_m A_m} \tag{1}$$

$$\varepsilon = \frac{d_t + d_m}{L} = F_{pt}\left(\frac{1}{E_t A_t} + \frac{1}{E_m A_m}\right) \tag{2}$$

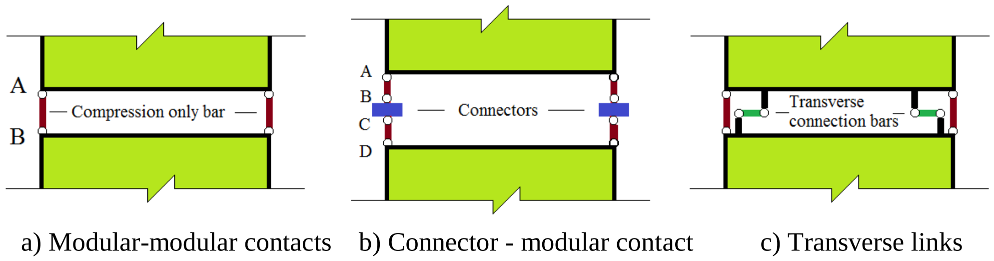


Figure 3. Connection between modules and connector

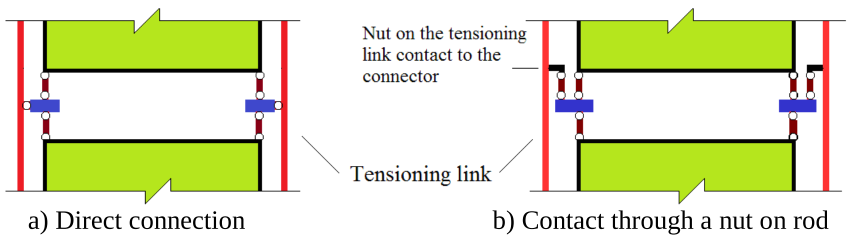


Figure 4. Connection between tie rods and connectors

2) Modular frame-connector contact: The contact between the modular frames in the vertical direction is modelled by mass-less, rigid, and compression-only bar elements, as shown in Fig. 3(a). Where the modular frames are connected through a connector, two compression-only bars are used at each connection, Fig. 3(b). The interaction between the modular frames and the connectors in the transverse direction can also be simulated, using transverse links, Fig. 3(c). The properties of the transverse links may be assigned to simulate different coupling behaviour between the tubular columns and the connectors, which may also vary before and after separation.

3) Tie rod-connector contact: The connection between tie rods and connectors can be modelled in a

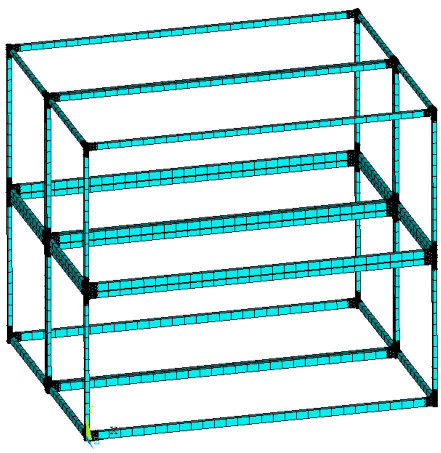
similar way as described above. Fig. 4(a) is the simple case where the tie rod directly connects to the connector. If the tie rod is attached to the connector through a lock-nut, a link element (compression-only bar) may be inserted between a node (the lock-nut) in the tie rod and the connector, Fig. 4(b).

4. SEISMIC RESPONSE OF THE MODULAR SYSTEMS

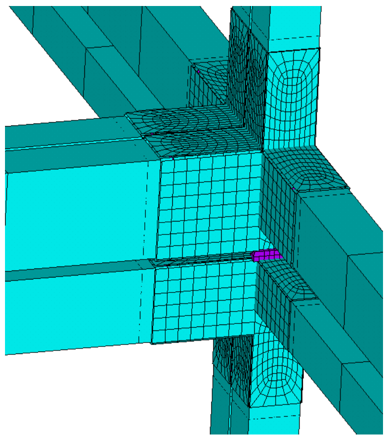
The PTMS system under consideration is typically used for low-rise multistory buildings in regions with low seismic hazard, and is not originally designed for specific seismic resistance. As such, the tubular columns themselves are considered to be strong enough to resist the nominal lateral loads without the need of resorting to additional resisting mechanisms, such as braces or shear walls.

Nevertheless, the PTMS has appreciable in-built seismic capacity. Firstly, each individual module is a well-formed structural unit, with rigidly welded joints made in a factory environment. The tubular steel frame of the module is designed to work as structural member in the overall structure. The horizontal shear force (inter-storey shear) can be resisted by the columns (and incorporation of additional bracing or shearing panels is possible). Secondly, the connectors by which adjacent storeys are joined via column-to-column connections are capable of transferring the lateral (shear) force between storeys. Thirdly, the tension rods and the pre-tensioning stresses tighten the assembly in the vertical direction, thus providing resistance to the tendency of overturning (global) and uplifting (along side column lines). However, the in-built seismic capacity of the current PTMS design could become insufficient when the system is used for high-rise buildings and subjected to larger seismic forces.

A study is therefore carried out to assess the seismic resistance capacities of the existing PTMS, using refined finite element models, typical of which is shown in Fig. 5. Based on the FE analysis, three failure modes of the PTMS under seismic loading are identified.



a) Global view of the FE model



b) FE model of connection region

Figure 5. FE model of a typical modular frame with 4 modular units (2-bay, 2-storey)

i) Module Structural Component Failure (MSCF): This failure can occur on the section of the main frame if a module is subjected to excessive seismic loading. In the current modular frame, this will mainly be bending failure of the tubular columns, as shown in Fig. 6. Because of the local enhancement from the horizontal beam at the joint, the column bending failure would occur slightly higher than the upper flange of the beam. As in typical multistorey frames, MSCF woud usually occur in the lowest storeys or at storeys where the lateral (storey) stiffness changes abruptly.

ii) Local Connection Failure (LCF): The vertical continuity of PTMS is provided by pre-stressing through the tension rods, in conjunction with column-to-column connectors. No welding or bolting connection is required between adjacent modular frames. However, in the event of large seismic loading, the connection region could experience local failure due to excessive concentrated force on the connection region. Fig. 7a shows a failure scenario of a tubular cross-section subjected to concentrated contact force near the end of the section. Moreover, relative displacement between the column and the connector causes complication in the load transfer path at the connection region, as depicted in Fig. 7b, thus affecting the integrity of the connection and even the entire system. LCF usually occurs at the lower storey of PTMS structure where larger shear force and uplifting force take place.

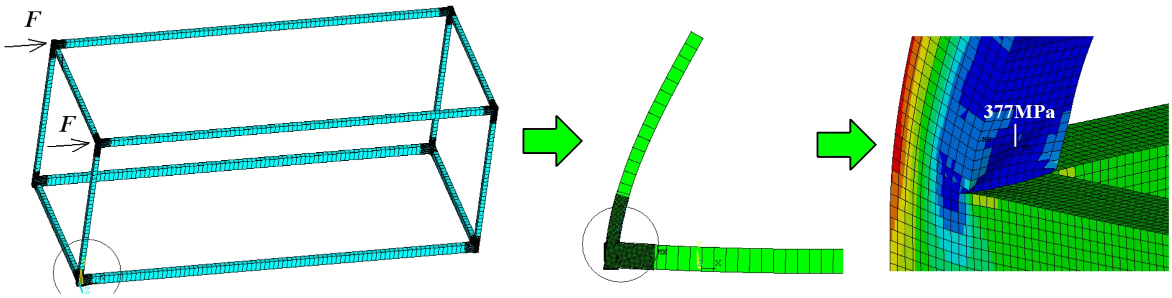
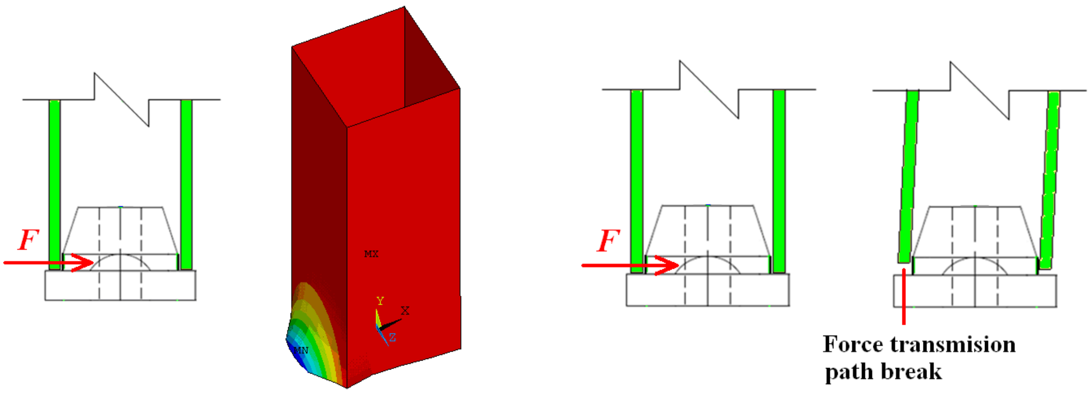


Figure 6. Typical MSCF failure in a column of modular frame

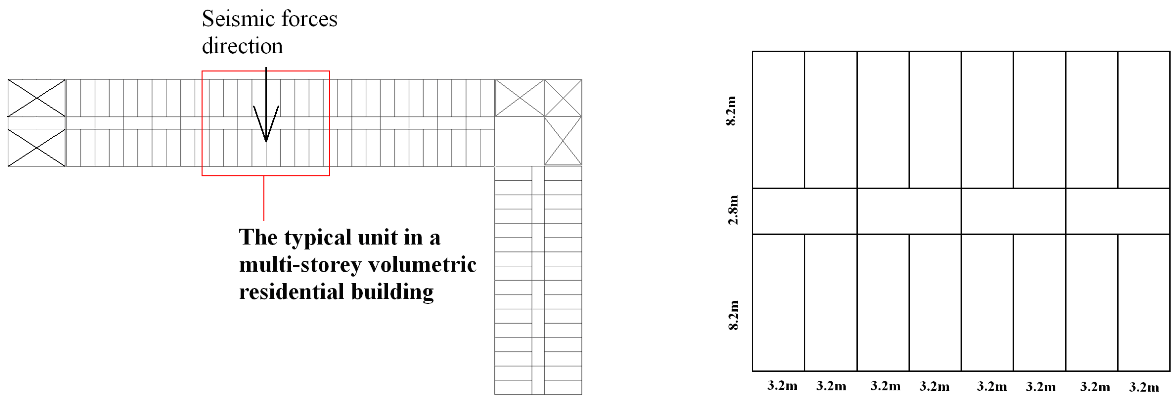


a) Failure due to concentrate loading b) Failure due to break of force path

Figure 7. Typical LCF at the connection region between modular units

iii) Tension Link Failure (TLF): The uplifting force and the tendency of separation between modules due to a horizontal seismic force is counter-balanced by the self-weight, along with the tightening effect due to the tension rods. For slender multistorey buildings, however, large additional tension force can be added to the tension rods, and when the total tension force exceeds the tensile strength of the rods, tensile failure occurs. Failure of the tension rods (TLF) is critical to the integrity of PTMS, as the tension links are the primary mechanisms tying the whole assemble of the modular frames in the vertical direction. TLF could also lead to large local deformation in the connection region due to module separation, and subsequently trigger LCF shown in Fig. 7b. The risk of TLF depends on the layout and dimension of the building.

Based on the refined FE model and the failure modes identified above, the seismic capacity of PTMS structures is studied. Fig. 8 gives the layout of a typical multi-storey PTMS residential building. A structural segment with four sub-units is isolated from the main building for the analysis. The dimension of the segment is shown in Fig. 8b. The permanent and live loads on the building are adopted from a practical design. The building is assumed to be located at a site with type-C soil condition (dense sand or gravel). The structural damping is assumed to be 2% and the seismic response (elastic) spectrum is taken from Eurocode 8.



a) A multi-storey residential building b) Representative building segment

Figure 8. A residential building constructed by volumetric modules

Frames made from the same modular units but with different numbers of storeys, ranging from 1 to 5 storeys, are analysed. Results indicate that:

i) for a single-storey building, the frame is assessed to be capable of resisting seismic load with PGA (peak ground acceleration) of the order of 0.35g, and is governed by MSCF failure mechanisms.

ii) the seismic resistance in terms of PGA reduces as the number of storeys increases. For the 5-storey frame, PGA capacity is assessed to be generally in a range of 0.15-0.2g.

iii) Except for the single-storey case, failure is dominated by LCF, followed by MSCF, while TLF is the most unlikely failure mode with its corresponding resistance being 3 times or more of the LCF.

Possible modifications of a PTMS system for enhanced seismic performance can be derived using the failure modes identified earlier. Since LCF tends to be the weakest link when the system is subjected to large seismic loading, tacking this type of failure should be the first priority. Because such failure is local, a simple and effective way can be applied to enhance the resistance. For example, the shear force concentrated on the inner wall of the tubular cross-section shown in Fig. 7a can be reduced effectively if the area of contact surface is increased. A larger contact surface also enhances the tolerance of the connection to the potential separation of the modules, thus enhances the robustness of the system.

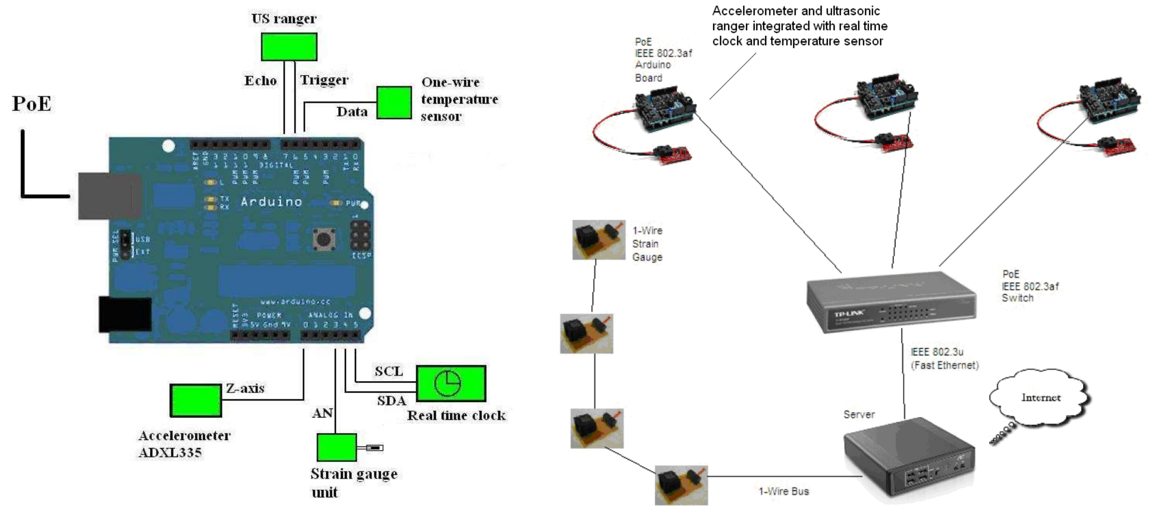
MSCF appears to be the second failure mode in PTMS. There are a number of methods to increase the structural resistance to MSCF. The most effective way is to add dedicated shear resistance components instead of increasing the cross-section of columns, such as using cross bracing bars or shear force resistant wall panels structurally fitted to the main modular frames. Although TLF is the least likely failure mode, however it bears much higher consequences and therefore the risk of such a failure should be minimised. Adding an additional vertical locking mechanism between modules could be a viable approach.

5. MONITORING THE STRUCTURAL CONDITION FOR A MODULAR SYSTEM

Since modular systems are primarily produced in a factory environment, it is advantageous for such systems to be equipped with building intelligence and structural health monitoring (SHM) systems. In fact, the development of a cost-effective SHM system is an integral part of a structural intelligence project for the PTMS system under consideration. The project aims to bring intelligence to PTMS by developing monitoring and control systems for energy efficiency, security, and occupant comfort, as well as structural health monitoring.

The design of the particular SHM system is based on the failure modes identified in the previous sections. The system consists of a number of selected sensors and dedicated data acquisition/processing programs to collect and evaluate data for the monitoring and assessment of the structural health and performance levels, including the serviceability as represented by the deflection and vibration levels.

The configuration of a typical sensor unit based on the microcontroller Arduino Uno is shown in Fig. 9. Arduino is an open-source electronics prototyping platform based on flexible, easy-to-use hardware and software. The platform can sense the environment by receiving input from a variety of sensors, through the interface of analog channels and digital channels. In the present system, the microcontroller on the board is programmed using C++ and the Arduino development environment (Arduino_website). The computation capability of Arduino enables the local data processing of the SHM system. The micro-controller is programmed to process the raw data and extract results of interest to be transmitted to a central station, thus reducing the data communication demand. The local processing capability of the SHM system is especially suitable for wireless communication.



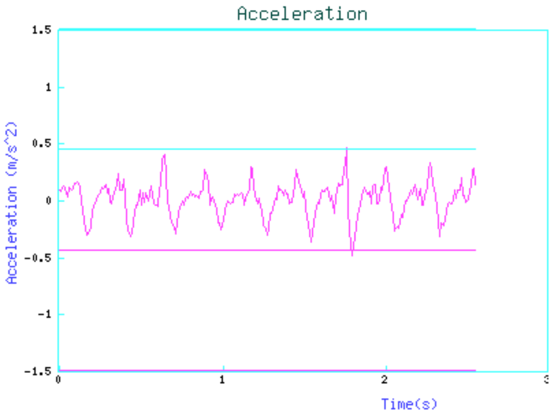
a) Sensor unit b) Data acquisition architecture

Figure 9. Architecture of sensor unit based on Arduino Uno and data acquisition system

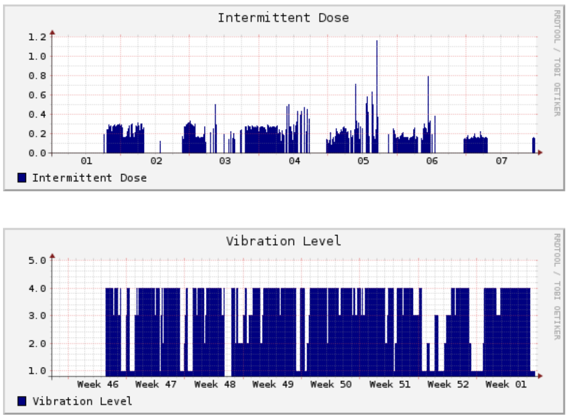
In the SHM system for a PTMS building, accelerometers (ADXL or BMA series) are employed to measure the real time vibration (acceleration) of the floor for occupant comfort assessment, and record the structural dynamic response in the event of an abnormal excitation such as during an earthquake. In the case of floor vibration assessment, the real time acceleration is processed by a subroutine on the Arduino and provides the floor vibration dose and level according to the British Standard BS-6742. The real time capacity is enabled by using a Real Time Clock (RTC) module interfacing with the microcontroller by I2C. An ultrasonic ranger module is also employed to measure the critical structural deformation, such as the deflection of floor or beam that is critical to the structural serviceability; or the module separation at the connection region that is critical to LCF and TLF. At the same time, the onboard program processes the raw data and provides a real-time structural health index. Temperature data are collected by a one-wire temperature sensor. Beside, a strain gauge pack is included to measure the real-time strain on critical structural members in the PTMS, for example a) the tensioning link for TLF, b) the ends of the column for MSCF, c) the connection region between modules for LCF, and d) the mid-span of beam with large span. The strain pack can be connected to the Arduino and perform processing locally, as shown in Fig. 9a; or it can be connected to the central processing station by via one-wire system, as shown in Fig. 9b.

The architecture of the SHM system comprises a single server gateway networked with multiple Arduino local processors. The real time clocks of the Arduinos are synchronized periodically with Network Time Protocol (NTP) packets from the server. The Arduino units are self-powered using

Power over Ethernet (PoE) with a suitable PoE switch and communicate directly to the server after each instance of local data processing using Hypertext Transfer Protocol (HTTP). The server then stores the results in a database, recording vibration level, intermittent dose, dose summation, acceleration, deflection level, strain and deflection. Examples of further server processing includes a real-time view of accelerations, and time series data of the results, which can be accessed via the Internet, are shown in Fig. 10.



a) Real time accelerations



b) Record of vibration level

Figure 10. Example monitoring results (accessible via Internet)

6. CONCLUDING REMARKS

The structural characteristics of a post-tensioned modular frame system, in particular the mechanisms against lateral loading, are investigated in this paper. A simplified modeling scheme is developed for such system, and it is shown that the scheme is capable of modeling the global behaviour as well as the special features relating to the installation of the pre-stressing forces and the redistribution of stresses between the main frame and the post-tensioning system under seismic loading. In conjunction with a refined finite element model, the basic failure modes of the PTMS buildings under seismic loading are identified and their general seismic capacities of PTMS buildings are assessed. In addition, a low-cost SHM system for the structural condition and performance monitoring is introduced as part of a comprehensive building intelligence system.

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