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Vibration Performance of Lightweight Cold-formed Steel Floors

R. Parnell[1], B.W. Davis[2], and L. Xu[3]

A study investigating the modal properties and dynamic response of several laboratory-constructed and in situ floors supported with cold-formed steel C-shape joists for floors was conducted. The tested floors were typical of residential mid-rise applications, with OSB, FORTACRETE® and cold-formed steel deck subfloors, both with and without lightweight concrete topping. Details including span, large lip-reinforced web openings, subfloor, topping, strongback and framing condition were varied to observe their influence on fundamental frequency, damping ratio and deflection. Suggestions for design and remediation of floors where vibration serviceability is a concern are given. Laboratory tested floor systems were generally found to be the worst-case scenario for natural frequency and damping ratio. Furniture and finishes were found to not appreciably change the performance of a floor system. The responses of the floor systems tested in this study were evaluated against the ISO 2631 limit for maximum acceleration and Onysko's static deflection limit, as presented in ATC Design Guide 1. The in situ floors examined were found to have performed within the acceptable range, as defined by the two criteria.

INTRODUCTION

The use of cold-formed steel floor joists has become increasingly popular for residential and commercial construction. This increased use can be partially attributed to the high strength-to-weight ratio of the joists, facilitating long, lightweight floor systems. Other benefits include rapid construction and reduced floor thickness. When joists with lip-reinforced web openings are used, ducts and pipes can be installed within the joist depth. Lightweight floor systems may be susceptible to certain vibration problems because there is less mass and lower structural damping than other equivalent systems, especially when an "open concept" layout is used (Hanagan et al. 2003; Murray 1998). These characteristics could result in the dynamic response of a

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[1] Research Assistant, The Canadian Cold-formed Steel Research Group, Dept. of Civil and Environmental Engineering, University of Waterloo, Canada

[2] Research Assistant, The Canadian Cold-formed Steel Research Group, Dept. of Civil and Environmental Engineering, University of Waterloo, Canada

[3] Associate Professor, The Canadian Cold-formed Steel Research Group, Dept. of Civil and Environmental Engineering, University of Waterloo, Canada

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floor system being greater in both amplitude and displacement, which is detrimental to vibration serviceability performance.

There is a need to quantify the performance of cold-formed steel floor systems in order to assess their vibration response in terms of the various acceptability criteria available for human comfort. Designing a floor system to control annoying vibrations can be challenging, and correcting inadequacies after construction is usually very costly (Allen 1990). Design methods for floor systems commonly used within the North American residential construction industry were developed for traditional lightweight wood framing, or heavy steel joist and concrete systems; and have not been adequately adapted for the specific characteristics of cold-formed steel members. There is also a need to study various floor framing construction details and their influence on vibration performance, in order to aid in design improvements and retrofit. Finally, the vibration performance of joists with large lip-reinforced web openings has not been previously studied.

This manuscript contains selected results from a study of cold-formed steel floor systems performed at the University of Waterloo, and various mid-rise residential sites in the United States. Several full-scale floor systems were tested, and their dynamic response measured. The influence of construction details, and in situ floor performance were investigated. Selected in situ floors are evaluated in this manuscript using criteria for acceleration and static deflection.

Floor Vibration Studies

Reiher and Meister (1931) conducted one of the earliest studies of human response due to floors subjected to steady-state dynamic loading, categorizing perception from “Not Perceptible” to “Very Disturbing”. Lenzen (1966) developed the Modified Reiher-Meister Scale, by reducing the severity of each category by a factor of 10, after modeling the floor vibrations as transient phenomena, rather than the harmonic excitations used by Reiher and Mesiter. Lenzen studied the dynamic and subjective response of steel joist and concrete slab floors and examined the influence of damping and the fundamental frequency on occupant comfort. Wiss and Parmelee (1974) investigated human response to floors excited by walking loads and provided an

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acceptability scale based on initial amplitude, vibration frequency and damping ratio. In the 1970's, Onysko conducted a field study examining several wood floors in houses which were designed using traditional span length based deflection requirements (Onysko et al. 1981). In several cases, the occupants were not satisfied with the vibration performance of the floors designed in this traditional manner, and a static deflection criterion based on the study results was developed (Onysko 1988). Lightweight floor vibration performance from walking and impulse loading was studied by Ohlsson (1988).

Laboratory testing specific to cold-formed steel joists was performed by Murray and others at the Virginia Polytechnic Institute where various individual system components and prediction methods were studied (Kraus and Murray 1997). Cold-formed steel floor system testing has been conducted at the University of Waterloo since 1998. The influence of various excitation techniques and construction details was studied (Xu 2000). Also, comparisons of frequency and stiffness were made between laboratory tests and both finite element, beam and plate models (Liu 2001). Recently, a paper discussing floor vibration testing techniques and modal analysis procedures was published in order to provide guidelines for future research (Hanagan 2005).

Acceptability Criteria and Design Procedures

Several engineering approaches for the design of floor systems that will satisfy occupant comfort demands have been developed from the results of the above studies, as well as numerous other studies. Two approaches are used, based on the properties of the floor systems. Floors with fundamental frequencies of less than 10 Hz are considered low frequency and are susceptible to resonant responses due to walking excitation. Floors with fundamental frequencies of greater than 12 Hz are considered high frequency expected to dissipate the individual impulses generated by footfalls without undergoing resonance. Floors with fundamental frequency values between 10 Hz and 12 Hz have been found to fall into a grey area where both high and low frequency behavior occurs (Brownjohn and Middleton, 2008). For high frequency floors, analysis of the transient response due to a single impact may be sufficient depending on the intervals between impacts and the damping of the floor system (Hu et al., 2001).

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Early models were based on a single degree of freedom beam, and considered one-way behavior only. The work by Onysko and Ohlsson involved developing an acceptability scale based on the responses of study participants, which may not translate easily to other types of floor systems and loading (Ohlsson 1988; Onysko 1988). The International Standards Organization has published guidelines for acceptable vibration levels for humans for various applications, including building design (ISO, 2007). Several design methods have incorporated the limiting acceleration values presented by ISO (Allen et al. 1999; Murray et al. 1997; Smith and Chui 1988). The one-way beam model was found to be inadequate for floors with low aspect ratios or low transverse stiffness, so a ribbed orthotropic plate model was developed (Smith and Chui 1988). It was identified that a resonant response may occur due to harmonic multiples present in walking excitation, and that the heel drop (or similar impulse excitation) may not be adequate for predicting overall floor response (Allen and Murray 1993).

Design procedures for low frequency floors can be applied with hand calculations, but over-predict the actual response due to the over-conservative application of a stationary excitation (Brownjohn and Middleton, 2008). Finite element methods that attempt to predict the response of a floor system to an applied load that is modeled after the mechanics of a walking human have been developed (Mello et al, 2008). Design procedures for high frequency floors can also be applied with hand calculations, but rely heavily on empirically calibrated coefficients. Pavic et al critically reviewed the CSTR43 method for high frequency post-tensioned concrete floors stating that it was an over-simplification of a complex engineering problem and that the only value of the hand calculation approach was that the calculations could be made by hand (2008). Again, the finite element approaches can be used to apply impulse loads to high frequency floors.

Two current design guides, readily used in residential floor system design practice, are: AISC/CISC Steel Design Guide 11, which is applicable to heavy steel joist and concrete floors (Murray et al. 1997); and ATC Design Guide 1, which has provisions for lightweight floors, and heavy steel joist and concrete floors (Allen et al. 1999). The dynamic and static calculation procedures in both guides are intended for a broad audience and use a hand calculation-style approach.

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EXPERIMENTAL INVESTIGATION

An experimental study was conducted to examine the following: 23 full-scale floor systems built in the laboratory at the University of Waterloo; 8 full-scale in situ floor systems built at the Dietrich Design Group (DDG) test facility; and 12 full-scale in situ floor systems built at several residential midrise buildings in the United States.

The main objectives of the investigation were to measure the dynamic characteristics of the floor systems tested and to assess the influence of changes in construction details on those characteristics. The in situ floor systems were designed to meet typical requirements for structural safety, fire resistance, noise transmission, and a maximum deflection serviceability requirement of L/480.

Laboratory Apparatus

All floor systems were supported by a heavy steel frame mounted on grouted beams, and reinforced with large, concrete-filled pedestals. The mass and stiffness of the frame was significantly greater than that of the floor system, and its influence was not considered. A brief description of the relevant components and capabilities will be presented. Details of the test frame can be found in previous publications (Davis et al. 2008; Xu and Tangorra 2007). The test frame accommodated floor widths of up to 4.88 m and adjusted to accept span lengths of up to 7.32 m.

The laboratory floor systems were tested with a free-support condition along the outer joists, and three different joist-end restraints. The joist-end restraints were selected to model balloon framing, platform framing and a simple support. Balloon framed floors span between the wall studs and are attached to each stud with a shear connection. To represent this condition with the laboratory apparatus, the webs of cold-formed steel stud members were attached to hot-rolled channels mounted on the test frame. The floor system was fastened to the flanges of the studs. Platform framed floors sit on top of the wall at each stud, and the span above the wall studs. To represent this condition with the laboratory apparatus, the floor rested on a 100 mm x100 mm wood support, which was mounted to the test frame. A superimposed load of 1.9 kN/m was applied above the bearing support to simulate the above-storey. To represent the simple support, the platform framing condition was used without the superimposed load.

Laboratory Specimen Details

Each floor system consisted of nine cold-formed steel joists, spaced at 610 mm on center. At the supports, the joist webs were connected to a proprietary rim track (1.90 mm thickness) with a punched clip-angle type shear tab. Traditional web stiffeners were not installed at the ends of the joists, the shear tab also acted as a web stiffener for the joists. The loads applied to the floor system during testing were not substantial enough to cause reduction of the gross section properties of the joists. The two joist types tested were:

- Dietrich CSW C-stud joists, 305 mm deep with 50.8 mm flanges, which are standard C-shape joists with stiffened flanges, with 101.6 mm x 38.1 mm elliptical openings spaced at 1.22 m on center along the neutral axis; and
- Dietrich TDW TradeReady® joists, 305 mm deep with 50.8 mm flanges, which are C-shape joists with stiffened flanges, with proprietary openings spaced at 1.22 m on center along the neutral axis. The openings are large, circular, lip-reinforced holes, 203 mm in diameter, which allow ducts, pipes and members to be installed within the depth of the floor joists.

All floors were constructed with blocking and strapping lines spaced every 2.44 m on center, perpendicular to the joist direction, resulting in 1 or 2 rows, depending on floor span. The blocking consisted of a cut joist section secured between the joists at every fourth joist spacing, and the strapping was a U-shape member screwed to the bottom flange blocking and every joist.

There were four subfloor configurations tested: two with a lightweight concrete topping, and two with bare sheathing. The subfloor configurations were:

- 19 mm oriented-strand board (OSB) with tongue and groove joints;
- 19 mm FORTACRETE® Structural Panel with tongue and groove joints;
- 19 mm FORTACRETE® Structural Panel with tongue and groove joints, topped with a 19 mm lift of

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LEVELROCK® Floor Underlayment; and

- 0.75 mm Dietrich UFS cold-formed steel form deck, topped with a 38.1 mm lift (to bottom flute) of LEVELROCK® Floor Underlayment.

FORTACRETE® Structural Panels are fiber-reinforced cement panels with tongue-and-groove edges that are non-combustible and designed to be installed in a similar fashion to OSB sheets. The unit mass for FORTACRETE® is 23 kg/m^2. FORTACRETE® panels are intended for use in topped and bare applications. LEVELROCK® Floor Underlayment is a gypsum-based, self-leveling floor topping that is intended for use in applications were a lightweight concrete is required. The UFS cold-formed steel form deck had flutes with a 14.3 mm depth and 63.5 mm pitch that were oriented in the transverse direction.

In subsequent sections: FORTACRETE® Structural Panels will be referred to as FORTACRETE® (abbreviated as FC); LEVELROCK® Floor Underlayment will be referred to as LEVELROCK® (abbreviated as LR); and UFS cold-formed steel form deck will be referred to as cold-formed steel deck (abbreviated as UFS).

Floor systems were tested with and without a gypsum board ceiling, which was fastened to steel resilient channels installed to the bottom flange of the joists in the transverse direction, at 305 mm on center (when ceiling was present). Some floor systems were tested with a cold-formed steel C-section strongback at mid-span, fastened to the joists using clip angles at every joist. Ceilings with Type X and Type C fire-rated gypsum board were tested. Figure 1 shows plan view and a cross-section of a typical floor built and tested for this study. Table 1 contains the specific construction details and characteristics of the laboratory floor systems tested in this study. All other aspects were identical between all floor systems tested. Additional details of the test specimens have been included in Davis et al., (2008).

In Situ Floor Testing Details

Testing of in the situ floor systems was designed to replicate the laboratory testing to the greatest degree possible. At the time of testing, finished drywall was in place for the walls and ceilings, and the concrete topping had cured. Subfloor assembly details, screw patterns, and blocking patterns were identical to the

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laboratory floors. Ceilings consisted of Type C gypsum board. All joists were 305 mm deep.

Notable variations in details between the laboratory and in situ floors include the following: all insulation, pipes, and ducting between the floor joists was in place; and floors were constructed using cold-formed steel balloon framing, and supported on all four sides. Floor widths varied significantly, but the impact of this was not directly investigated in this study. In order to make relevant comparisons, this study examined floors with ceilings fastened to the joists directly with resilient channel (RC). Some floors had ceilings with 2 layers of gypsum board. Floors tested with a drop ceiling are not discussed in this manuscript. Table 2 contains the in situ floors examined in this study, and their comparable details.

TEST PROCEDURE AND ANALYSIS

Test Methods

This test program was based on components of previous floor vibration tests performed at Virginia Polytechnic Institute (Kraus and Murray 1997) and at the University of Waterloo (Davis et al. 2008; Xu and Tangorra 2007). The heel drop and sandbag tests were used to measure the natural frequency and the damping ratio of the floor system. The heel drop excitation was provided by an 81.8 kg man standing at the center of the floor system, impacting the floor with his heels. The sandbag test was employed to validate the measurements from the heel drop test. The excitation was provided by a 10 kg sandbag falling from a 305 mm height onto the center of the floor system.

The walking test was used to measure the root mean squared (RMS) acceleration response for the entire excitation period of each floor system due to walking excitation. This test was developed to provide quantitative measurements of the floor system's response to realistic occupant activity. The test was performed by an 81.8 kg man continually walking from one edge of the floor to the opposite; in both the joist and transverse directions.

The deflection test was used to measure the maximum static deflection of the floor under a concentrated load of 1 kN at mid-span. This method was chosen so that the maximum deflection measured would correspond to