Stiffness Criteria and Dynamic Serviceability of Light-Weight Steel Floors

Critère de rigidité et comportement dynamique en service de planchers légers en acier

Steifigkeitskriterien und Schwingungsverhalten unter Gebrauchslasten von leichten Deckenkonstruktionen

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SUMMARY

Cold-formed thin-walled members and trapezoidal steel sheeting are frequently used for walls and roofing today. The use of such components in floor structures will require special detailing and design for dynamic footstep loading to ensure good serviceability. Floor springiness and vibration behaviour is analyzed. Proposed design parameters and their interpretation are described. Specific problems related to thin-walled elements such as low local rigidity are discussed.

RÉSUMÉ

Les profilés minces formés à froid ainsi que les panneaux de tôle trapézoïdale sont de nos jours fréquemment employés dans la composition des parois et toitures. L'utilisation de tels composants dans les planchers requiert une conception et un dimensionnement particulier pour un cas de chargement dynamique produit par une personne qui marche sur ce plancher, et ce, afin d'assurer une bonne aptitude au service. Le comportement vibratoire du plancher ainsi que sa souplesse sont analysés. Suit une description des paramètres proposés pour une étude détaillée, ainsi que leur interprétation. Des problèmes spécifiques aux profilés minces, comme par exemple la faible rigidité locale, font l'objet d'une discussion.

ZUSAMMENFASSUNG

Kaltgeformte dünnwandige Profile und Trapezprofilbleche werden heute sehr oft für Wände und Dächer verwendet. Wenn eine solche Bauweise für Decken gewählt wird, muss bei der Gestaltung und bei der Berechnung auch dynamischen Lasten von Fussgängern Rechnung getragen werden, um eine gute Gebrauchsfähigkeit zu gewährleisten. Die Elastizität und das Schwingungsverhalten von solchen Decken ist untersucht worden. Vorgeschlagene wichtige Parameter für eine derartige Konstruktionsberechnung werden beschrieben. Besondere Probleme solcher Elemente, wie die örtlich geringere Steifigkeit, werden diskutiert.

1. FLOOR VIBRATION AND SERVICEABILITY

1.1 Introduction

The limitation of springiness and floor vibrations is often governing the design of light-weight floors. For residential and office buildings the dynamic footstep load from people in motion is the most difficult one to handle at the design stage since this kind of load is likely to occur at any position. Consequently design for footstep loading concerns all parts of the floor structure, whilst for instance the design for dynamic machinery loads may include local stiffening, resilient mounting etc.

Traditionally excessive floor vibrations have not been a major concern to the design engineers. Very often good vibrational response has been believed to be achieved only by ensuring a certain stiffness due to a distributed load, e.g. deflection from a distributed load has been limited to a certain fraction of floor span. There are many examples showing that this is not necessarily sufficient.

Since floor vibration is very likely to occur in light-weight structures with low local rigidity and with a pronounced orthotropy with regard to bending rigidity, light-gauge steel floor structures unfortunately are candidates for being 'problem floors' if no special care is taken by the designer. In other words; when thin-walled cold-formed members or sheeting are to be used in floor structures one has to forget about strength (which of course must be checked in the end) and start the design process by creating a stiff structure with respect to a concentrated dynamic force at an arbitrary location.

The acceptable floor vibration level is usually determined by human sensitivity to vibration, but sometimes also by sensitive equipment like computers etc. Human sensitivity to vibration depends on a large number of parameters. The dependence of time is very strong, which means that short-term strongly damped vibrations may have many times higher amplitudes than stationary, continuous vibrations and still be rated as being less disturbing. The activity of a disturbed person is also cruical. A walking person accepts much larger vibrations than a person who is reading a paper.

1.2 Engineering interpretation of footstep induced vibration problems

Complex problems of the actual kind must be substantially reduced and simplified in order to achieve a more clear picture of the governing relations. This is the background to the following somewhat simplified description of selected relations and properties involved in footstep induced floor vibrations and their disturbing effects on people.

The contact force from a walking person is illustrated in fig.1. As can be observed this force can be characterized as a stationary dynamic force of the broadband type provided that the horizontal walking velocity is assumed to be small. However, the time history also contains impulsive parts of a more transient kind as well.

The frequency distribution tells that the major part is low-frequent (<6 Hz) and above 6 Hz the force intensity decreases inversely proportional to the frequency.

The impulsive parts of common footstep force time histories as well as forces from occasional jumps are to be considered as impacts. The structural response to impact load can roughly be said to be inversely depending on the structural mass activated. A high transverse bending rigidity enables a larger floor area (and mass) to participate in the initial impact response.
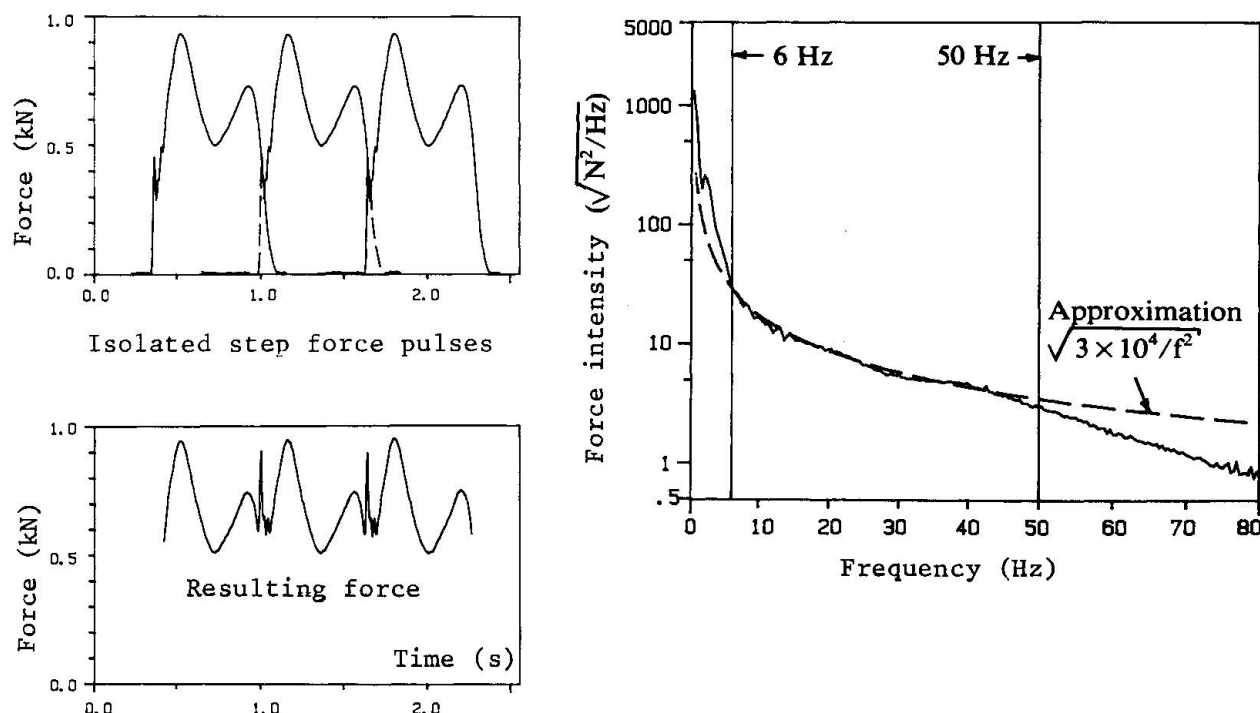
Figure 1 Footstep force time histories and force intensity (= square root of spectral density). After |4|.

Typical joist floor structures are of the one-way type, which means that they are strongly anisotropic. This is not a good property since it leads to a large number of closely spaced resonances. Most floors can be modeled as grid systems for static and dynamic analysis. Fig.2 shows static deflection and eigenmodes together with a flexibility plot for a joist floor.

Several conclusions can be made from the properties illustrated by fig.2. Firstly, the common approach to civil engineering dynamic problems, that it is sufficient to consider the fundamental mode only, seldom applies to this kind of structures. Secondly, an increase of the transverse bending rigidity of joist systems is often more effective than an increase of joist depth. The third conclusion is based on the force spectrum in fig.1 together with the flexibility frequency function in fig.2; If possible the fundamental frequency of a floor structure shall be chosen essentially higher than the upper frequency limit of the major force components ($\simeq$ 6 Hz). This means that the calculated lowest eigenfrequency should be at least 8 Hz for an unloaded floor. Although this cannot be achieved for very long-span floors, most light-weights floor structures can meet this demand.

Modal relative damping c/c_{cr} is most important for floor vibrations but it is usually not controlled by the design engineer. Experimentally determined values for c/c_{cr} vary approximately between 0.6% and 1.6% for laboratory floor specimens, but values up to 5 to 10% occur occasionally for floor structures in finished buildings. Although damping in finished buildings shows very large scatter one should be slightly suspicious to the very high damping values that sometimes are presented. Damping is a good property in two different ways; it reduces the vibration amplitude from stationary loading and it reduces the duration of large amplitudes after an impulsive load.

The human response to vibration is a complex matter. Two facts are the most important ones here. The human response to *sinusoidal* excitation is believed to be equally severe if the vibration *velocity* amplitude is the same, provided that the

frequency of the sinusoid is higher than 8 Hz. For lower frequencies, vibration acceleration seems to be a better measure on the disturbing effect. The human response to *impulsive* vibration is known to be heavily dependent on the decay rate. In other words, an initially larger vibration can be rated as less severe if the decay rate is higher.
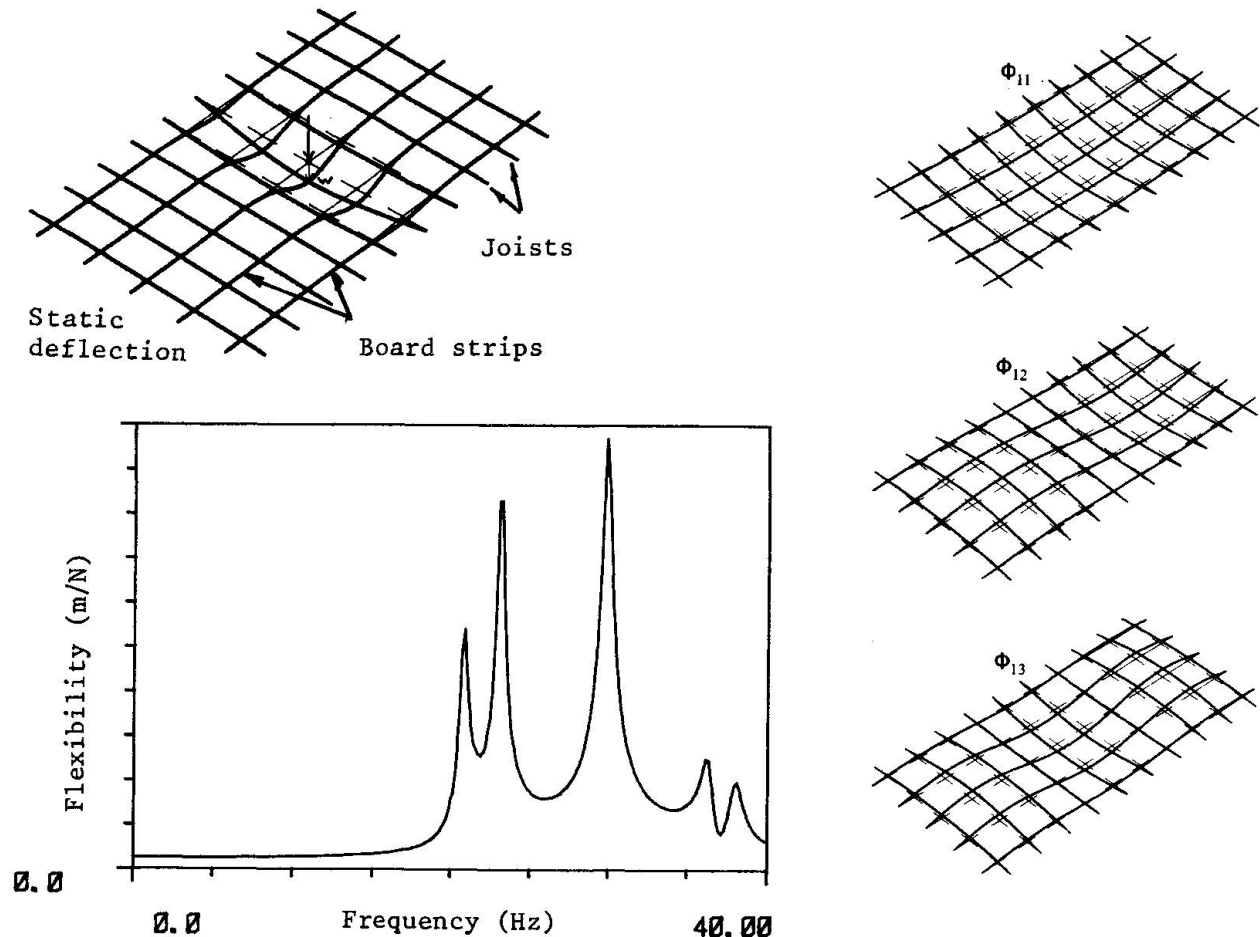

Figure 2. Typical "one-way" joist floor properties: Static deflection shape, frequency-dependent flexibility and corresponding mode shapes of vibration.

2. PROPOSED DESIGN METHOD

A procedure for the design of floors with respect to springiness and footstep induced vibration has been presented in |5|. The method applies to floors with a fundamental frequency ≥ 8 Hz and it is material independent. The design procedure is relatively simple to use because several design aids (flow-charts, diagrams etc) are provided. It is, however, outside the scope of this paper to describe it in any detail. Only the design parameters and their interpretation will be mentioned here.

The proposed design parameters to be calculated are the following:

a) Static deflection w from a concentrated force = 1 kN
b) Initial impulse velocity response h'_{max} from a unit impulse = 1 Ns
c) Damping coefficient $\sigma_0 = (c/c_{cr}) \cdot f_1$
d) Stationary vibration velocity w'_{RMS} from the force spectrum in fig.1

The static deflection (a) should preferably be related to the most pliant location, typically at midspan between two joists. The initial impulse velocity response (b) is illustrated in fig.3. This quantity should be rated together with the damping coefficient (c) according to the same figure. The damping coefficient σ_0 is a somewhat odd damping parameter. The reason for using it here is that it provides a measure of the decay rate with respect to *time* regardless of the actual frequency and that this is relevant for the human response.
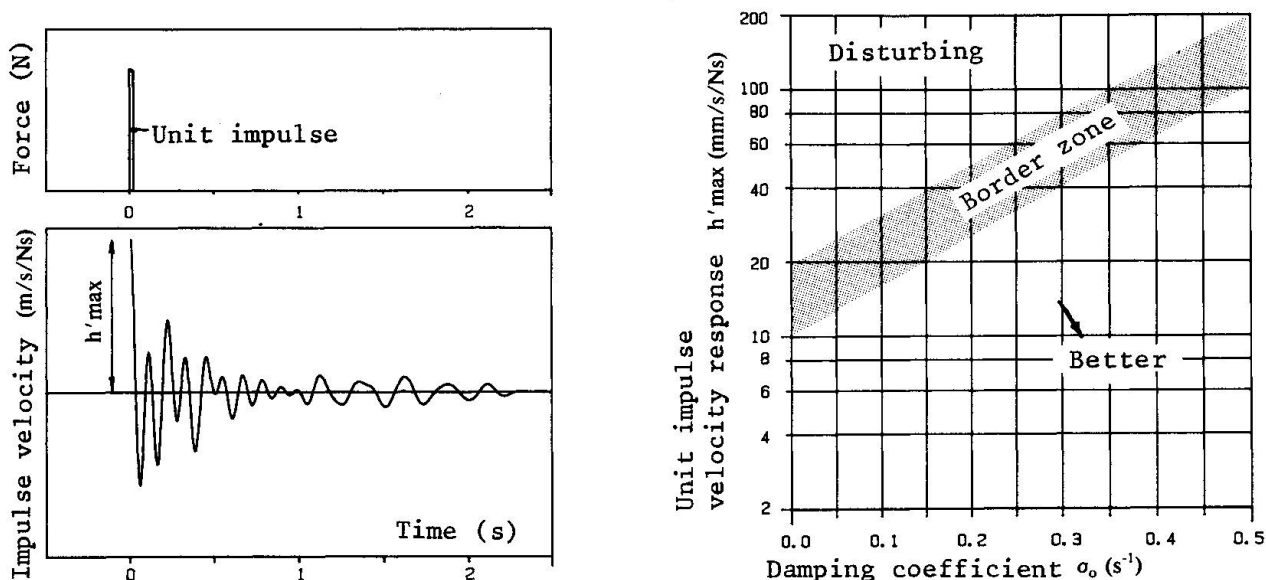

Figure 3. Illustration of impulse velocity response (left) and diagram for rating of floor impulse response (right).

The vibration velocity (d) is a calculated RMS-value for the vibration velocity generated by a dynamic stationary force with footstep force spectral properties as shown in fig.1.

The interpretation of the different design parameters should briefly be that the parameters(a),(b), and(c) together govern the degree of springiness and susceptibility to impulse vibration while parameter (d) is a measure of the severity of continuous vibration from more enduring pedestrian load.

3. STEEL FLOOR TYPES AND PROPERTIES

3.1 Overview

Steel floors can be divided into different groups with respect to the different kinds of structural components used. The following categories may be used:

1. Main structure consisting of hot rolled beams and welded girders supporting pre-fabricated concrete elements.

2. Composite structures with concrete slab cast on site on top of trapezoidal steel sheeting.

3. Trapezoidal steel sheeting supporting "dry" flooring of some kind, e.g. chipboard or plywood.

4. Cold-formed steel joist systems supporting the same kind of dry flooring.

The first type is today the most common one in Sweden. The second kind is very common in many different parts of the world and |1| gives an excellent guide to the subject.

The floor types 3 and 4 are not common yet. There is, however, a great inte-
rest i Sweden for such light-weight structures and this paper is mainly directed
to them as well. In order to faciliate, floors of group no.3 will be called
"trapezoidal floors" and those in group No.4 "joist floors". Joist floors are for
instance treated in |2| and |3|. Trapezoidal floors are rarely found in the lite-
rature. The author has, however, been involved in the development and testing of a
couple of such floor systems. One example is mentioned in |4| as specimen "TRP".

3.2 Light-gauge trapezoidal and joist floor properties

The global characteristics of these cold-formed floor structures are comparable
to the properties of light-weight joist floor structures of other materials, e.g.
timber and plywood beam systems etc. The properties which are special for cold-
formed members are to be found within the areas of local flexibility, flexibility
of joints and the stiffness of mechanical fasteners. The lack of high local rigi-
dity of many cold-formed members origins from the fact that they have usually been
developed to carry as large *distributed load* as possible. Another reason is that
the cold-forming technique does not permit sharp angles of the member cross section.

Two facts about footstep induced deformations of a floor structure are essential
here. The vertical deflections of the floor surface are very small. In the vicini-
ty of the foot, deflections of the order 1-3 mm usually occur. In other areas
smaller deflections occur both *upwards* and downwards. The size of these smaller
distributed deflections are governing the dynamic stiffness experienced by a wal-
king person. This distributed deflection pattern is composed by the different
excited mode shapes together and is most important. Considering the fact that many
areas of residential and office floors are practically unloaded (open spaces), the
conclusion must be that the relevant stiffness value for a given member or joint
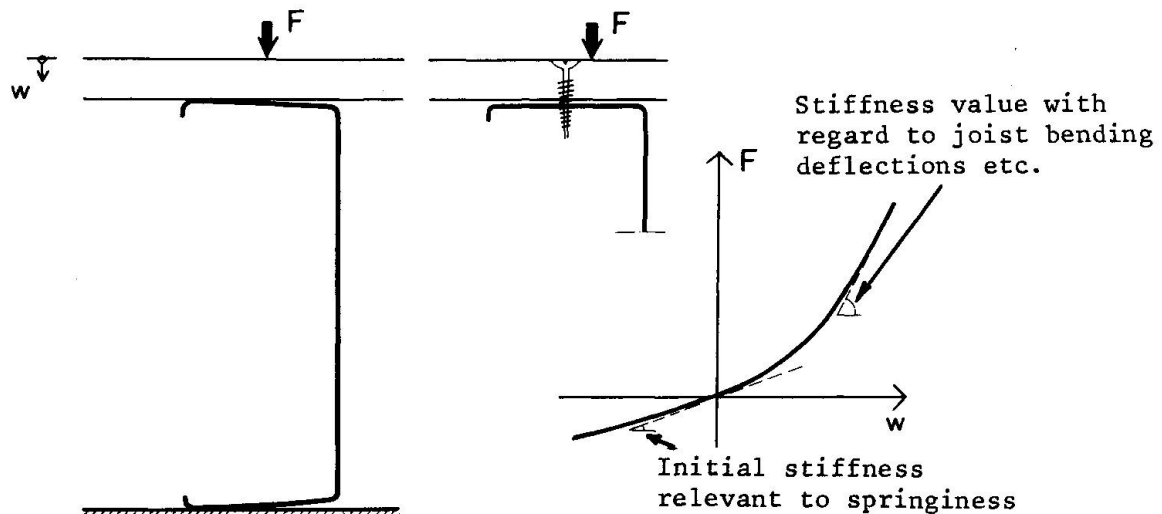is the very *initial stiffness in either direction*, c.f. fig.4.

Figure 4. Illustration of low initial rigidity due to flange plate bending or bad
function of self-tapping screws. F = force, w = deflection.

In fact there are numerous joint types which may show low initial stiffness ,
especially when considering that the dynamic forces sometimes are directed upwards.
One must also bear in mind that the ceiling mass, e.g. from gypsum boards etc, may
be quite large and to avoid internal low-frequency resonances the ceiling must be
relatively rigidly fastened to the floor structure.

Some of the rigidity problems may of course be avoided by local stiffeners. Fig.5
illustrates some unconventional methods for such stiffening. They may serve as an
inspiration for the development of new components which ensure highly rigid per-

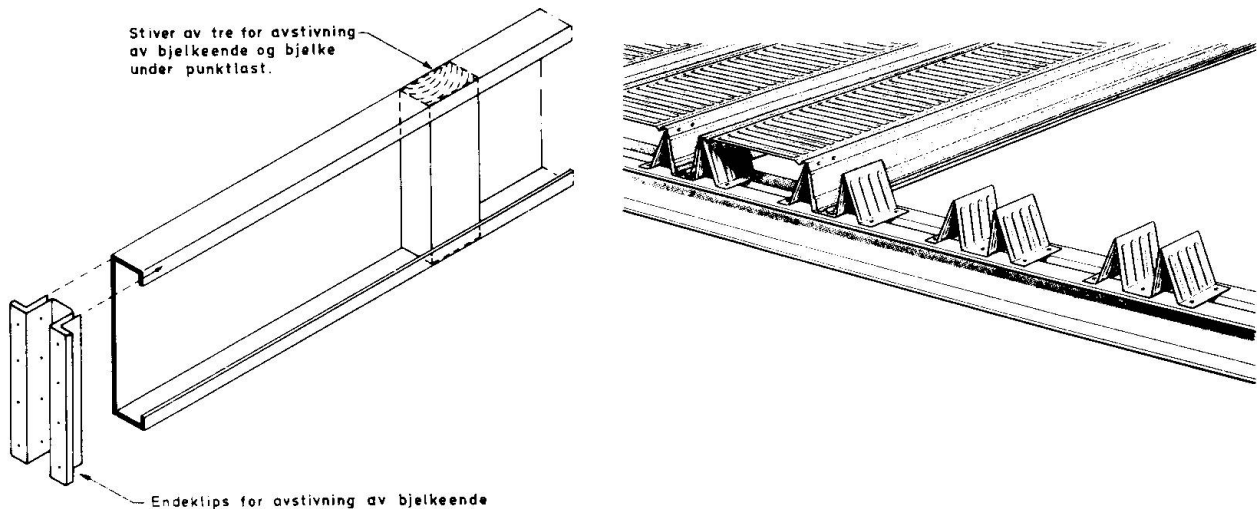formance for cold-formed structures. Such development is badly needed.

Stiver av tre for avstivning
av bjelkeende og bjelke
under punktlast.

Endeklips for avstivning av bjelkeende

Figure 5 Example of local stiffeners (after |2|) and trapezoidal steel sheeting
(PLANNJA) occasionally used as floor structural element.

4. CONCLUDING REMARKS

The use of trapezoidal and joist floors will be more dependent of different ser-
viceability limit state properties than of load bearing capacity. Generally
speaking, a structure which has been optimized with respect to one specific task
usually will be malfunctioning in another situation until a re-design has been
carried out. This should be taken as a challenge, which hopefully results in the
development of thin-walled steel floor structures with suitable properties, such
as high bending rigidity in two perpendicular directions as well as high local
rigidity. Artificially added and controlled high damping properties and the ab-
sence of noisy steel plate contact connections are other desirable goals for
the development of steel floor structures.

REFERENCES

1. Chien E.Y., Ritchie, J.K., Design and Construction of Composite Floor Systems.
   Canadian Institute of Steel Construction, Markham Ontario 1984, Canada.

2. Engebretsen Per Arne, Bjelkelag med stålprofiler av tynnplater (Floors with
   cold-formed steel joists). Report No.30, The Norwegian Institute for Building
   Research, Oslo 1980, Norway.

3. Linehan P.W., Kudder R.J., Wiss J.F., Dynamic and Human Responce Behavior of
   Cold-Formed Steel-joist Residential Floor Systems. Fourth International Spe-
   ciality Conference on Cold-Formed Steel Structures; "Recent Research and Deve-
   lopments in Cold-Formed Steel Structures vol II", Univ. of Missouri-Rolla,
   Saint Louis 1978, USA.

4. Ohlsson Sven, Floor Vibrations and Human Discomfort. Chalmers Univ. of Techno-
   logy, Div. of Steel and Timber Struct., Ph.D. Thesis, Gothenburg 1982, Sweden.

5. Ohlsson Sven, Svikt, svängningar & styvhet hos bjälklag - Dimensioneringsmeto-
   der (Springiness, Vibrations and Stiffness Properties of Floors - Design Methods)
   The Swedish Council for Building Research, Publication T20:1984, Stockholm 1984,
   Sweden.

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