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Measurement of Floor Vibration

Mesures des vibrations de planchers

Messung von Deckenschwingungen

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SUMMARY

Recently, the Architectural Institute of Japan compiled comprehensive guidelines for evaluating the habitability of buildings with respect to vertical floor vibration by making reference to exhaustive related research findings in the past. The authors, having conducted measurements of vertical floor vibration of a large number of buildings over many years, examine the reasonableness of the AIJ's evaluation guidelines by using related field data and describe a practical design concept that ensures sound floor beams giving special attention to the beams supporting office floors.

RESUME

La Société des Architectes du Japon (AIJ) a dernièrement établi des directives très complètes pour l'évaluation de l'habitabilité des immeubles en ce qui concerne les vibrations verticales des planchers, sur la base de l'ensemble des résultats de travaux menés par le passé. Les auteurs, qui ont procédé pendant de longues années à des mesures de vibrations verticales des planchers d'immeubles, étudient le bien-fondé des directives d'évaluation de l'AIJ en faisant appel aux données disponibles dans des domaines connexes et ils décrivent les concepts qui, dans la pratique, assurent la robustesse des poutres de plancher, en s'intéressant tout particulièrement aux poutres soutenant les planchers des bâtiments commerciaux.

ZUSAMMENFASSUNG

Jüngst hat das Architectural Institute of Japan umfassende Richtlinien für die Bewertung der Bewohnbarkeit von Gebäuden hinsichtlich vertikaler Deckenschwingungen erstellt, indem auf erschöpfende Forschungsergebnisse der Vergangenheit Bezug genommen wurde. Die Autoren, die Messungen der vertikalen Deckenschwingungen in einer grossen Anzahl von Gebäuden über viele Jahre durchgeführt haben, untersuchen die Verhältnismässigkeit der AIJ-Bewertungsrichtlinien durch Verwendung einschlägiger Felddaten und beschreiben ein praktisches Bemessungskonzept, das insbesondere für Bürogebäude ausreichende Deckenträgerquerschnitte liefert.

1. MEASUREMENTS OF FLOOR VIBRATION

In Japan, the achievements accumulated in many years through exhaustive researchers on the structural design method and the habitability evaluation method, both related to serviceability of buildings, were compiled in comprehensive form results. The fruit of such compiling efforts can be seen in the two books published lately by Architectural Institute of Japan (AIJ), which has always played a leading role in setting out the nation's building design criteria. One related to the former is Standard for Limit State Design of Steel Structures (draft) published in 1990 while the other related to the latter is Guidelines for the Evaluation of Habitability to Building Vibration published in 1991.

As a new design method alternative to the conventional allowable stress design, the limit state design (LSD) employs "limit state design method" which prescribes that structures be designed according to the design criteria based on the limit state of steel structures. In this method, two types of limit state are established: one is the limit state as to the structural safety of buildings and the other is the limit state as to the serviceability and habitability of buildings.

Of these two, the serviceability limit state design requires that the following three principles be observed as design basics: 1. design considering the limit strength of a structure during use; 2. design considering the limit deformation of a structure during use; and 3. design considering the lateral sway and vibration of floors due to floor vibrations and wind force and also adverse vibrations due to any other causes.

Of the three principles mentioned above, the one concerned with the design consideration for serviceability and habitability of steel buildings mentioned in Item 3 prescribes that "the design shall provide means to deal with floor vibrations and lateral sways of a building as necessary. In such design, proper working loads and acceptable levels of vibrations, lateral sways, etc. shall be set out based on the required service and functional performance of the building." The basic concept has had to be expressed in this way because the performances required of buildings vary with their intended purposes, sizes, shapes, etc. and therefore are not amenable to a uniform definition.

The Guideline for Evaluation published in 1991 comprises two kinds of criteria, i.e., one for the vertical vibration of the floor and the other for the lateral vibration of the building. While the habitability in a broad sense comprises such factors as safety, functions, sanitation/hygiene and comfort, the guidelines primarily aims at securing daily living comfort which is habitability in a narrow sense, and in order to allow as much design freedom as possible, there are intended to provide a general guide for performance evaluation rather than to define acceptability strictly.

As for the evaluation of habitability related to vertical vibration of building floors, the guidelines provide the criteria for performance evaluations in terms of displacement amplitude and acceleration amplitude for three types of vibrations which have different characteristics and for different types of buildings classified by their intended uses. As for the intended purposes of buildings, the following three categories are considered: living rooms and bedrooms in residential buildings; conference and drawing rooms of office buildings; and general office spaces of office buildings. The guidelines also prescribe that responses to floor vibrations be evaluated by three kinds of methods which include predictions analyses and actual measurements. As for the vibration-related criteria set out by AIJ, the relationship between vibration frequencies and displacement amplitudes were specified in "Standard value for the building structural design to present vibration-induced damage (plan)" deliberated in 1959, and the criteria contained therein had been left intact for about 30 years until they were replaced by the aforesaid new criteria. As for the restriction of beam deformation, AIJ's Design Standard for Steel Structures published in 1970 specified that the displacement under the total load should not exceed 1/300 of the span. This means that buildings in Japan kept on becoming greater in span and height while no up-to-date criteria concerning the serviceability of building floors were established. In the meantime, measurements as well as theoretical and experimental researchers related to this subject were carried out by a number of researchers and practicing engineers, and this paved the way to the compilation of the aforesaid two AIJ Standards.

The authors, too, accumulated substantial measurement data on the vertical vibrations of floors of many buildings intended for various purposes through their more-than-thirty year involvements in the design of such buildings. In this report, some of such measurement data will be presented by limiting the data to those on the office buildings where human footfalls are thought to be a principal cause of floor vibrations. Following this, practical means to deal with such vibrations will be introduced from a viewpoint of structural design and the applicable performance evaluation criteria will be examined. Lastly, some consideration given to the design be the authors to prevent hard-to-predict vibration nuisances will be described.

2. STRUCTURAL DESIGN OF FLOOR BEAMS

As preparatory means to design sound floor beams free of adverse vibrations, the authors have been accumulating measured floor vibration data on a variety of buildings. Since the acceptable levels of floor vibrations are believed to vary with the intended purposes of buildings, the authors will introduce in this paper a number of cases limiting the floor beams to those supporting office floors where vibrations are mainly created by human footfalls. Floor beams must above anything else be designed to have functions to support working dead loads and live loads and transfer them to the foundations by way of columns. In areas like Japan where seismic force is a predominant factor, floor beams are often designed to be in the form of girders which serve as elements in aseismic framework; hence, in designing such beams, not only their capacity to carry the lateral force due to an earthquake but also their bending rigidity which affect the lateral rigidity of a building structure must be considered.

Therefore, cross sectional areas of floor beams with relatively short spans are governed by the bearing capacity and rigidity required by aseismic design, and in many of such cases the rigidity required of the floor beams to resist vertical floor vibrations may consequently be regraded as negligible.

For this reason, buildings having relatively long spans accounted for the majority the buildings whose floor vibrations were measured by the authors. Consequently, most of the buildings in which floor vibrations were measured by the authors were steel structures having composite beams except a small number of buildings which had prestressed concrete floor beams. In these buildings, the steel beams were in most cases connected with reinforced concrete slabs by means of shear connectors to increase rigidity. Headed studs were generally used as shear connectors. The design method for this type of composite beams was formulated by AIJ as design guidelines in 1975. Since steel beams and concrete slabs jointly resist bending moments, composite beams display higher load-carrying capacity and rigidity than steel beams acting alone.

Fig. 1 shows a typical composite beam. Fig. 2 shows moment inertia, which are the indices of bending rigidity of members, for various sections of H-shaped steel beams and comparable composite beams. The figure is intended to show, by using slab thicknesses and effective widths of composite beams as parameters, to what extend moment inertia can be improved by adopting composite beams. This remarkable increase in bending rigidity as shown in the figure testifies clearly that composite beams are effective for preventing nuisances caused by vertical floor vibrations.

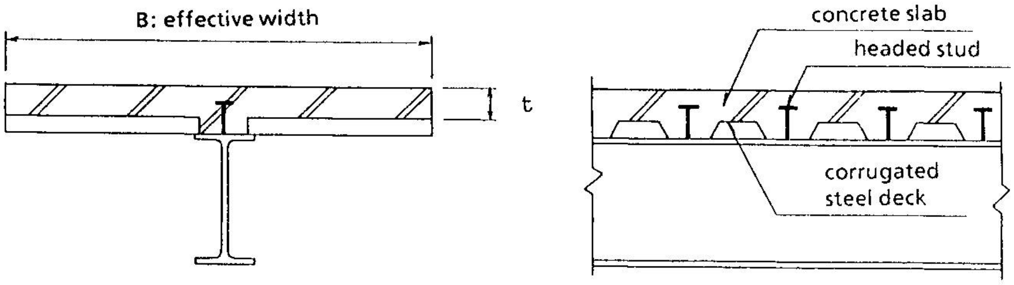

Fig.1 Composite beam

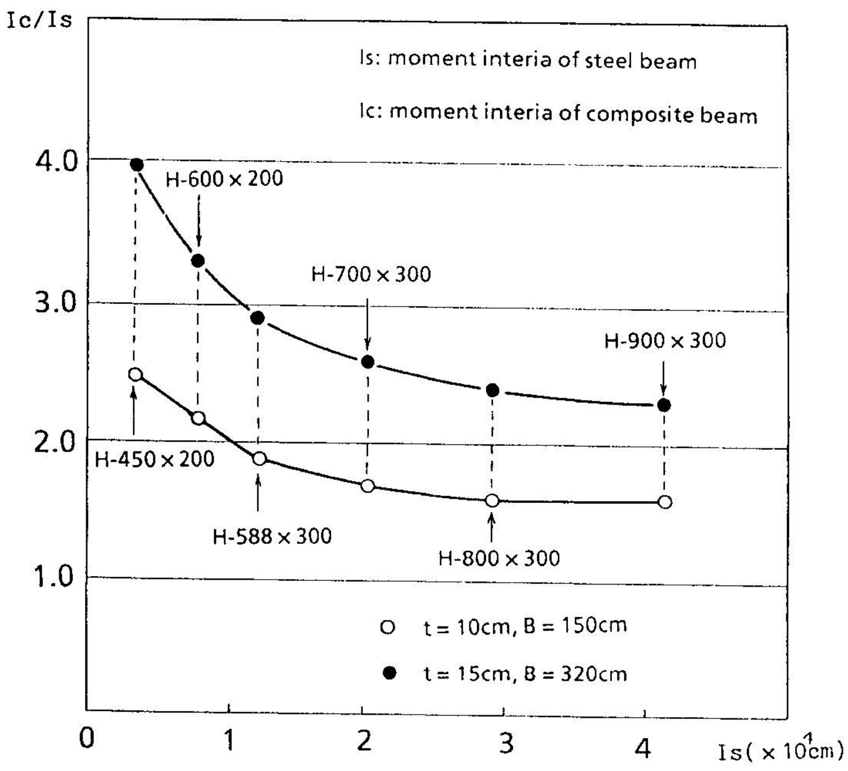

Fig.2 Increase in flectial rigidity of composite beam

3. MEASUREMENT RESULTS AND EVALUATIONS

For the purpose of measurements, the authors caused the floors to vibrate by using one of the following three methods: 1) dropping of a sand-bag, 2) forced vibration by means of an oscilator, and 3) human footfalls. Fig. 3 shows the measured frequencies of vibrations caused by Method 1) in which a bag containing compacted sand weighing 30kg was dropped by gravity to the floor to cause vibrations when the basic properties and damping constants have to be measured in order to study beam-floor interactions under vibration. A formula indicting the relationship between the vibration frequencies and the deflections due to dead loads is included in the figure.

In Fig. 4, the frequencies thus obtained are compared with the computed frequencies.

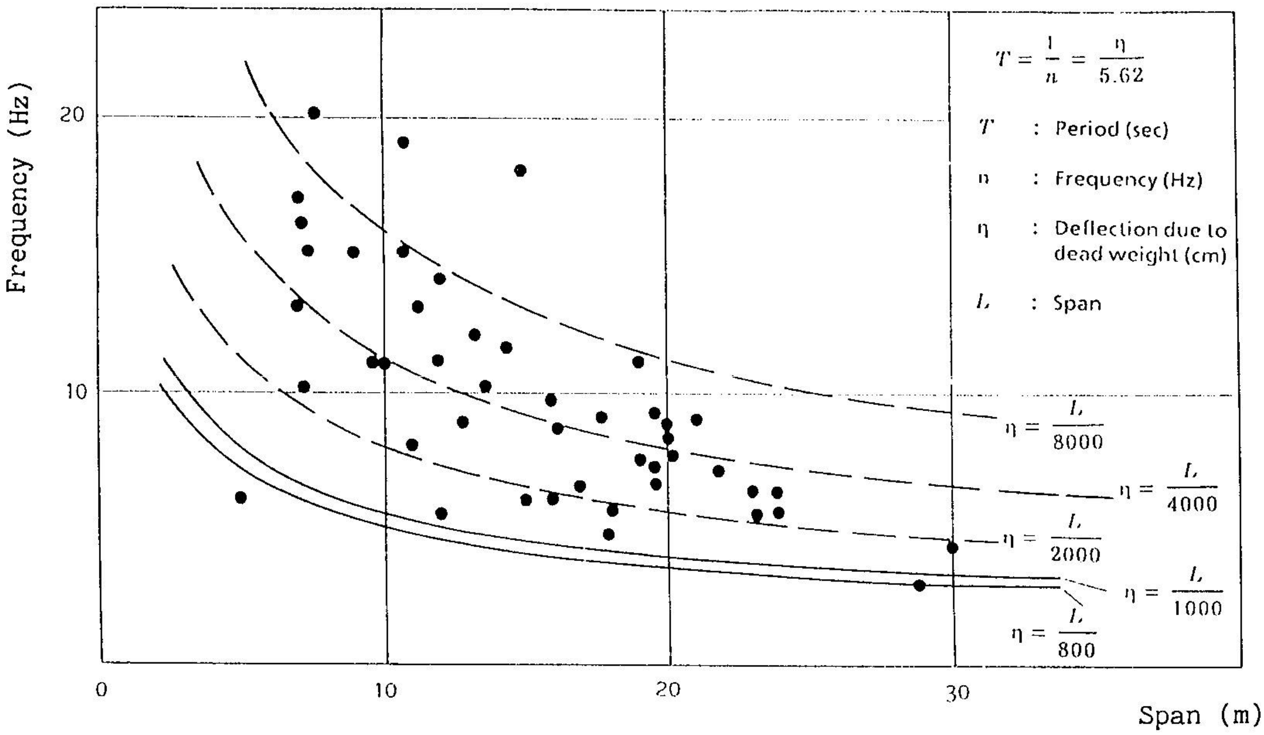

Fig.3 Measurement frequency VS. span

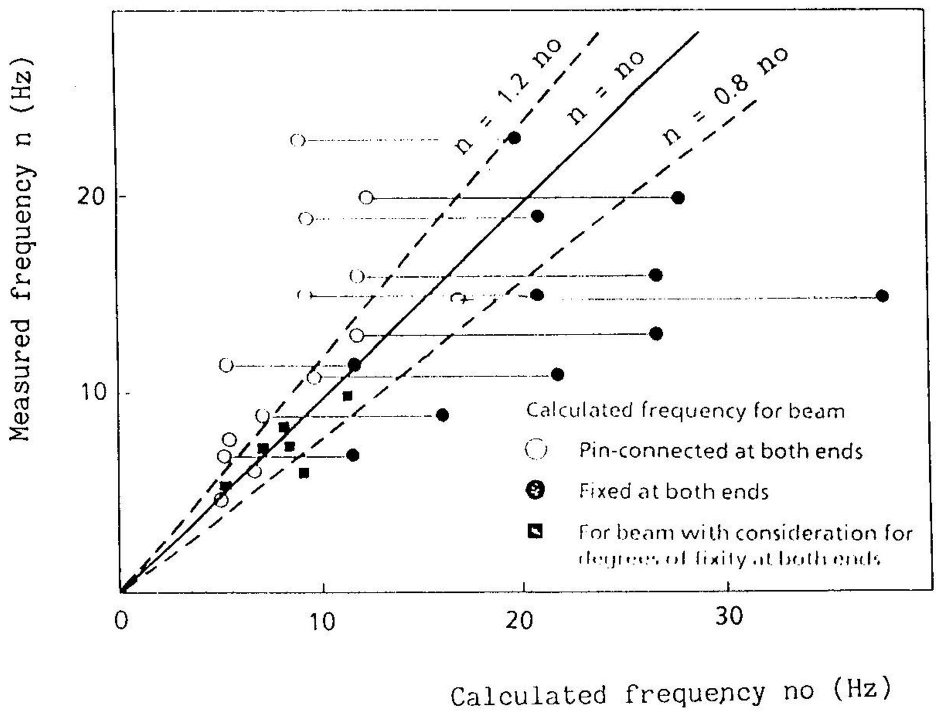

Fig.4 Frequency of floor beam

Most of these floor beams were rigidly connected to the columns to form a rigid frame; however, good agreement was seen between the measured and the computed values in case the conditions of end fixty were accurately evaluated. Where it was difficult to accurately determine the conditions of end fixity, the computed frequencies were given for both cases, i.e., for hinged connection and fixed connection, and the measured values were found to be somewhere between the computed values for these two cases.

Fig. 5 shows the relationship between the measured dynamic deflections of the floor beams when the floor supported by them was subjected to footfalls given by two persons and the vibration frequencies. This experiment was conducted to simulate a case where the floor supported by such beams was used as office space. Although the results obtained were rather erratic being influenced by the walking paces, etc. of the persons, all the plotted values, which were obtained by averaging the dynamic deflections measured several times, may be taken as data that verify sound floor beams reasonably free from adverse vibrations. The standard line V-5 as set out in AIJ Recommendation 1991 for the floor beams supporting a floor to be used as office space and the recommended line proposed by the authors at IABSE WCII workshop 1989 are indicated in the figure on a comparative basis. Both the proposed lines embrace the upper limits of the measured values obtained thus far be the authors and they agree with each other almost completely; therefore, they may be considered good formulas that serves practical purposes well under the present circumstances.

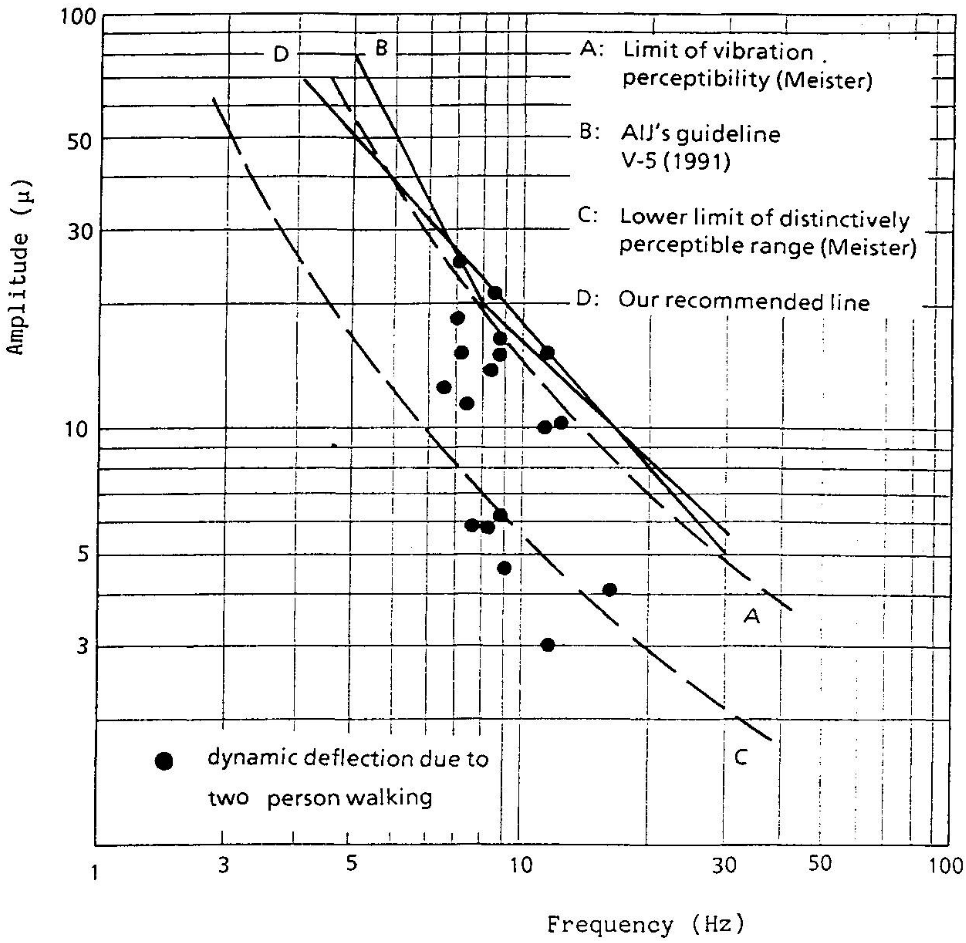

Fig.5 Measured dynamic deflection due to person walking in office building

In connection with the method of calculating dynamic deflections, dynamic deflections of beams due to lateral impacts as obtained by Timoshenko's formula given below and the comparable measured values are shown in Fig. 6.

$$\delta_d = \delta_{st} + \sqrt{\delta_{st}^2 + 2h\delta_{st}\frac{1}{1 + \alpha \cdot \frac{W_1}{W}}} \qquad (1)$$

where,

δst : static deflection of the beam caused by a falling object

δd : dynamic deflection due to impact

h : falling height

W1 : total weight of floor beam

W : weight of falling object

α : 17/35 (for simple beam supported at both ends)

The value of α indicated above is the one obtained for a beam simple-supported at both ends. For a beam fixed at both ends, the applicable value is 13/35.

Further, the impact caused by footfalls of two persons was obtained from the test data available in Japan and also from the results of researchers based on the law of conservation of momentum. Namely, predicated on a conclusion that the impact caused by the footfalls of one person is equal to that caused by a object weighing 3kg dropped by gravity from a height of 5cm, conversion was made to a case of the footfalls of two persons, and W=6kgf and h=5cm were obtained from Fig. 6.

While the measured values were generally lower than the theoretical values thus obtained, in some cases the former turned out about 1.5 times the latter.

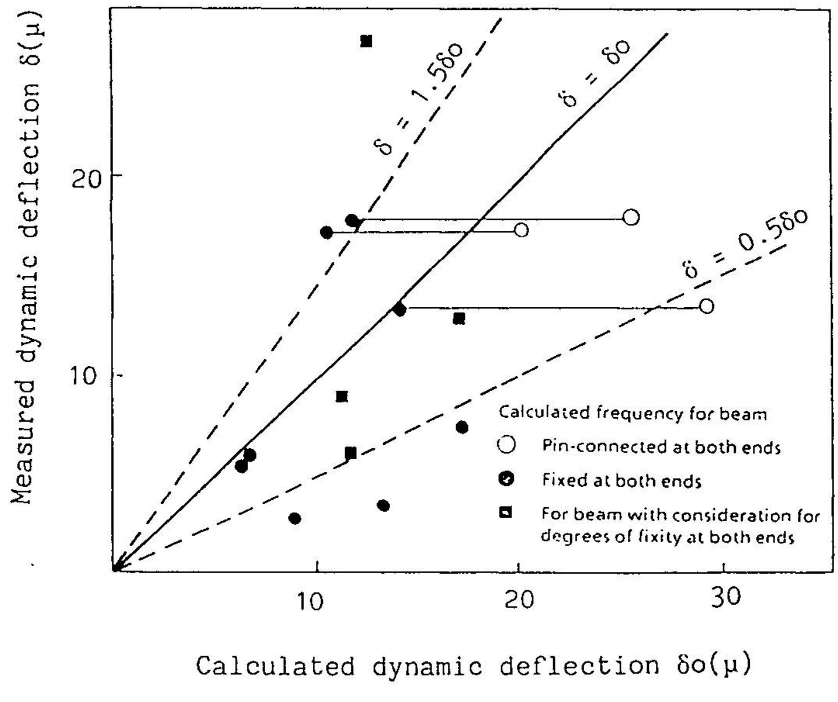

Fig.6 Dynamic deflection due to two person walking

4. CONCLUSIONS

The results of studies described above indicate the typical guidelines for office buildings given in AIJ's Recommendation 1991 correspond very well with the measured results and therefore are considered adequate. Further, under the present technological circumstances, it is proposed that the following be considered when studies as to vertical vibrations of floor beams supporting office spaces are to be made at the design stage.

1) Vibration frequency of floor beams should be computed. For computations, the fixty at beam ends should be defined as correctly as possible.
2) Dynamic deflection of floor beams due to human footfalls should be computed by Formula (1).
3) Evaluation should be made according to Standard Line V5 (AIJ Recommendations 1991) shown in Fig. 5.
4) Also, from Fig. 3 it may be considered reasonable for practical purpose to restrict the deflection of floor beams due to their deadweight to below 1/800~1/1,000 of their spans.

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