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Dynamic response of infilled frames incorporating a sliding base device

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It is known that the use of infilled panels in frames is advantageous for the aseismatic capacity of a structure. However, the high stiffness of the infill might induce sensitivity to certain values of earthquake loading. This difficulty can be resolved if a sliding base device is suitably incorporated between the base of the infilled frame and the foundation. In this Paper, emphasis is placed on the improved dynamic behaviour of the infilled frame that results when the frame is mounted on a sliding base. Because the inelastic stiffness of the sliding base during the shaking process is difficult to determine analytically, it is determined instead by experiment, on the basis of which an equivalent non-linear foundation model is established. The infilled frame and the equivalent non-linear foundation are then assembled and analysed by the ADINA program. Experimental and analytical results show that the combined system retains high structural stiffness under normal loading conditions while sustaining a greatly reduced response to base excitation. It is therefore concluded that the adoption of such a system can increase the ability of a building to resist both wind and earthquake loads.

Introduction

The proper use of infilled panels incorporated within the plane of a frame, termed an infilled frame, has been shown to be of great practical and economic significance in resisting seismic, wind and blasting loads. The advantageous behaviour of an infilled frame is derived mainly from the interaction that develops between the infilled panels and the frame in that:

(*a*) the in-plane bracing action of the panels greatly increases the stiffness and strength of the infilled frame as compared with the bare frame
(*b*) the progressive yielding of the interface between the frame and the panels retains the ductility of the structure, and
(*c*) the progressive cracking of the panels dissipates the energy when excessive vibration occurs.

2. Mallick and Severn[1] performed an experimental study on the dynamic characteristics (e.g. energy dissipation capacity and damping ratio) of infilled frames. Sokal[2] reported a study on the natural periods of infilled frames. Kahn and Hanson[3] and Bertero and Brokken[4] carried out an experimental study on the

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cyclic behaviour of infilled frames with different interface conditions. Palsson *et al.*[5] studied the dynamic response of buildings with heavy claddings. The studies[4, 5] on the infilled frames subjected to earthquake loading have shown that the response sensitivity of a structure may be substantially increased because the increased stiffness of the infilled frame may shift the fundamental frequency of the structure towards the higher energy part of the earthquake spectrum. In this context, a contradiction exists between high stiffness on the one hand, and high strength on the other, both of which are inherent properties of an infilled frame.

3. It is well known that a base isolator can reduce the earthquake loading transmitted to a building or plant. Hence, if a base isolator is suitably incorporated in the infilled structure, the aforementioned contradiction might be resolved. A simple method for base isolation is the sliding base, where special pads which have both Coulomb and visco-elastic damping properties are placed at the interface between the structure and the foundation. The sliding interface is locked rigidly by the Coulomb force when the excitation is a moderate earthquake or wind. When a strong earthquake occurs, the shearing force at the base will overcome the frictional force and sliding will then occur. Hence the earthquake loading transmitted to the building is limited by the frictional coupling. At the same time, the repeated sliding will dissipate the vibration energy and reduce the vibration level, and in this way the sliding base acts both as a safety valve and a damper. If it is adequately designed, the infilled frame will have both high strength and stiffness during normal conditions, but will sustain only low earthquake loading during extreme conditions.

4. Base isolation technique has been of interest to civil engineers in recent years for aseismatic structures[6, 7] and as Coulomb friction is an inherent characteristic of structural interfaces, it is regarded as probably the most economical technique for aseismatic structures. Experiments[8, 9] have shown that the infilled frame possesses heavy damping and strong non-linear stiffness when it is subjected to a loading near collapse level. However, when the loading is one-half to one-third of the collapse load, the stiffness curve can be considered approximately

Notation

c	equivalent damping constant of interface between frame base and foundation
F_1	frictional force of pad 1
F_2	frictional force of pad 2
$\mathrm{sgn}(\dot{x}_0)$	$= \dot{x}_0/\lvert\dot{x}_0\rvert$
$f(x_0, t)$	non-linear reaction force between frame base and sliding pad
k	equivalent spring constant of interface between the frame base and the foundation
k_1	equivalent spring constant of pad 1
k_2	equivalent spring constant of pad 2
m_0	mass of the base
$Q(t)$	base shear of frame
u_0	displacement of the foundation, i.e. ground movement displacement vector of the frame
x	displacement vector of the frame
x_0	relative movement between the frame base and the foundation
$\mathbf{1}$	vector $\mathbf{1}^T = (\mathbf{1}, \mathbf{1} \cdots \mathbf{1})$
$\mathbf{C}$	damping matrix of the frame
$\mathbf{K}$	stiffness matrix of the frame
$\mathbf{M}$	mass matrix of the frame

linear. Therefore, if the sliding base can reduce by half the earthquake loading transmitted to the building, the structure will behave linearly and can be more realistically analysed by a linear FEM program, resulting in great saving of computer time. Furthermore, as the earthquake loading is reduced by the sliding of the base, the damage to the building is minimized.

5. There are two key points in applying such a vibration-reducing technique. One is the design of a Coulomb force-control device,[10] and the other is the development of a method for analysing the structure–sliding base system. This Paper is concerned with the latter.

Analytical procedure

6. Consider an infilled frame which is mounted on a base isolation system. An idealization of the structure–sliding base system is shown in Fig. 1. The equations of motion of the infilled frame and the base respectively for ground excitation are

$$\mathbf{M}\ddot{X} + \mathbf{C}\dot{x} + \mathbf{K}X = -\mathbf{M1}(\ddot{x}_0 + \ddot{u}_0) \tag{1}$$

and

$$Q(t) + m_0(\ddot{x}_0 + u_0) + f(x_0, t) = 0 \tag{2}$$

where

$m_0(\ddot{x}_0 + \ddot{u}_0)$ = inertia force on the base mass
$f(x_0, t)$ = shearing reaction force between the base and sliding pad
$Q(t)$ = base shear force of the upper frame structure

7. The relative movement x_0 between the base and the foundation is the unknown in the non-linear equations (1) and (2), which must be solved simultaneously by a step-by-step integration finite element program for non-steady excitation. In this Paper, the emphasis is on the influence of the sliding of the base on the response of the upper structure (the infilled frame), which can be considered as a linear structure for small deflexions, as stated earlier. The infilled frame has a large number of degrees-of-freedom, and is most readily analysed by a general linear finite element program. The reaction force, $f(x_0, t)$, between the base and the sliding pad, is a non-linear function of x_0, which varies during loading and unloading of the sliding base. Although the sliding base has only a small number

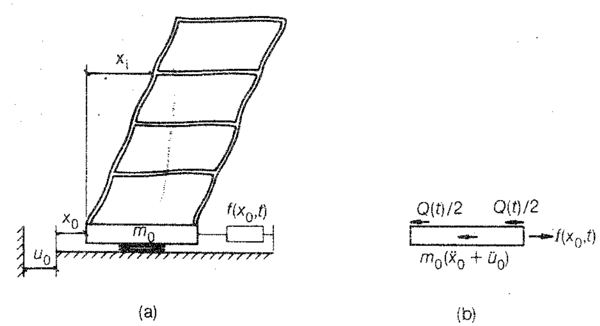


Fig. 1. (a) Idealization of the system; (b) equilibrium of forces on base

of degrees-of-freedom, its behaviour is not known and must be determined in the first instance by experiment. The infilled frame and the sliding base are therefore considered as two substructures, and dynamic analysis of the system consists of three steps:

(*a*) The mode solutions of the infilled frame are obtained by finite element analysis and checked by dynamic response tests. Through the correlation of analytical with experimental results, a modified and more accurate mathematical model of the infilled frame is established.

(*b*) The dynamic behaviour of the sliding interface has to be measured by a cyclic loading test, from which a mathematical model can be established.

(*c*) Finally, the two substructures are assembled and the response of the coupled system is analysed by the automatic dynamic incremental nonlinear analysis (ADINA)[11] program.

8. An infilled frame is a composite structure composed of a steel frame and infill panels. For small deflexions, reinforced concrete behaves as a linear material. Hence, three kinds of linear elements in the ADINA have been used in the dynamic analysis: the steel frame and the base beam are represented by three-dimensional beam elements, the infill panel by rectangular plane elements and the connecting bolts by one-dimensional truss elements. Because the excitation is limited in the plane of the model, all degrees-of-freedom out of the plane are restrained.

9. Each panel consisting of the infill is divided into a net of rectangular plane elements. In order to reduce computer time, the accuracy of the rectangular element solution has been tested by comparing the results obtained for different meshes, and a suitable mesh finally selected for the dynamic analysis.

10. At the interface between the frame and the infills, the plane elements of the infill and the beam elements of the frame have respectively two and three degrees-of-freedom at the nodes. To connect the nodes of these two different elements, the displacement relationship between the nodes of the frame and the infill is established by means of the displacement constraint equations, whereby the 'slave' displacements of the infill are related to the 'master' displacements of the frame by the actual conditions at the interface.

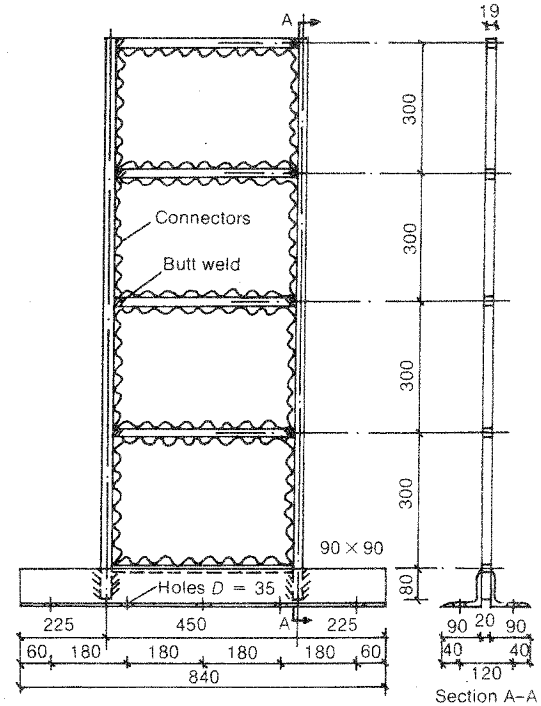
11. The ADINA program has the capability of distinguishing non-linear elements from linear elements. As the infilled frame is assumed to behave linearly in the case considered, the stiffness matrices of the linear elements are required to be formed only once. Dynamic computation on the ADINA program is carried out by a time domain step-by-step procedure.

Natural frequencies of infilled frames

Experiment

12. The dynamic tests on the infilled frames were carried out to obtain the natural frequencies, which were then compared with the calculated results.

13. Three four-storey models were constructed, one of which was a steel frame without infill. The other two models had shear connectors and were infilled with micro-concrete, having 5 mm maximum size aggregate, 0·62 water/cement ratio and 5·0 aggregate/cement ratio. All the infilled models were provided with two layers of No. 17 SWG wire mesh representing light reinforcement of 0·56% of the concrete cross-section. Their construction and dimensions are shown in Fig. 2.



Summary of steel frames

Frame mark	Column size, mm	Beam size, mm	Number of frames
0	19 × 9·5	19 × 19	1 Bare frame
1	19 × 9·5	19 × 19	1
2	19 × 19	19 × 19	1

Fig. 2. Construction of frame (with shear connectors) (dimensions in millimetres)

The average value of the modulus of elasticity for the concrete was $1{\cdot}5 \times 10^5$ kg/cm^2, obtained from six ϕ150 × 300 mm cylinder tests.

14. To reduce the fundamental frequency of each model, some lumped weights were welded at the joints of the frame. Each model was welded at the base to a pair of 90 × 90 × 9 mm steel angles, which in turn were bolted on to a heavy steel base. The experimental arrangement for testing the frames is shown in Fig. 3, and a block diagram of the apparatus in Fig. 4.

15. A continuously sinusoidal sweep signal was fed by an oscillator to an electromagnetic force vibrator through an amplifier to excite the model, the exciting frequency being monitored by a digital counter. At first, the search for natural frequencies was carried out by gradually raising the sweeping frequency and

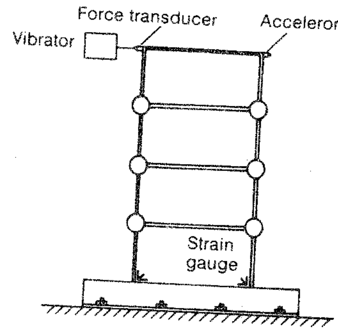


Fig. 3. Experimental arrangement for measuring natural frequencies

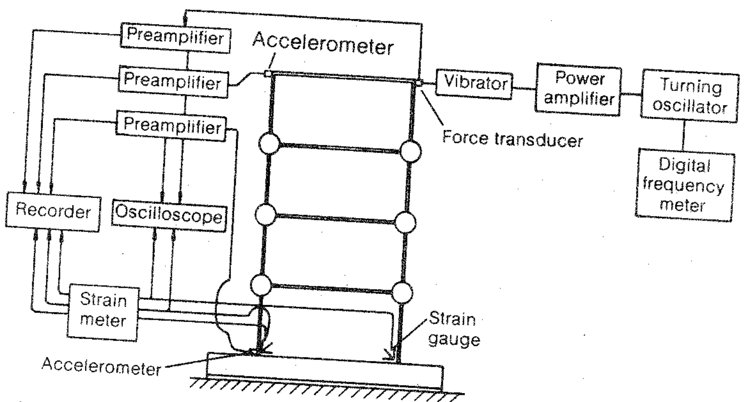


Fig. 4. Block diagram of vibration equipment

looking for the peak response on the screen of an oscilloscope. Next, the sweep was turned to a position around the resonance frequency, using a finer discrete frequency sweep to record all the response signals which were near the resonance frequencies on a magnetic tape. Finally, these signals were analysed by an HP 5420 signal analyser to determine the natural frequencies more accurately.

16. Hammer impact testing was also carried out. The impact to the model was produced by using a rubber hammer through a force transducer which was fixed on the model. The response was measured at different points on the model, and the signals were recorded at the same time. The transfer function of the model was then analysed by an HP 5420 signal analyser. An example of the transfer function curve, together with the results from the sinusoidal sweep, is shown in Fig. 5.

Comparison of measured and computed natural frequencies

17. At first, the base beam of the frame was assumed perfectly rigid. Although good agreement was obtained between the results of experiment and analysis for the bare frame, a large discrepancy (>40%) was observed for the infilled frame.

The discrepancy was attributed to the relative flexibility of the base beam compared with the infilled frame. In the bare frame, the second moment of inertia of the base beam was two orders higher than that of the frame. However, the infill increased the stiffness of the structure two orders higher, and the base beam could no longer be considered rigid. By taking into account the flexibility of the base beam, the results obtained from calculation were much improved, and a comparison of the natural frequencies is shown in Table 1.

Dynamic characteristics of the sliding interface

18. To design an aseismatic structure mounted on a sliding base, it is essential that the characteristics of the sliding interface are determined by base excitation so that a mathematical model of the sliding interface can be established. This can be done by using the same set-up and instruments as are shown in Figs 4 and 6. The force-displacement curve (Fig. 7) was automatically recorded on the console of the control system of the actuator. This curve can be separated into two parts as shown in Fig. 8, where Fig. 8(a) is a bilinear hysteretic curve normally used to represent the non-linear behaviour of a base isolator, and Fig. 8(b) represents the action of frictional force.

19. To analyse the interaction effects of the frame–sliding base system, an equivalent mechanical model is developed (Fig. 9). Since two kinds of pad, one steel and the other rubber, are inserted between the interface of the frame and the foundation, there are two frictional spring elements in the mechanical model: $\pm F_1$ represents the frictional force between the frame and the steel pad, and $\pm F_2$ represents that between the frame and the rubber pad.

20. Because the spring constant $k_1 \gg k$ and $k_1 \gg k_2$, when the base excitation is small, the frame is locked rigidly on the base and behaves as an ordinary cantilever structure. Hence

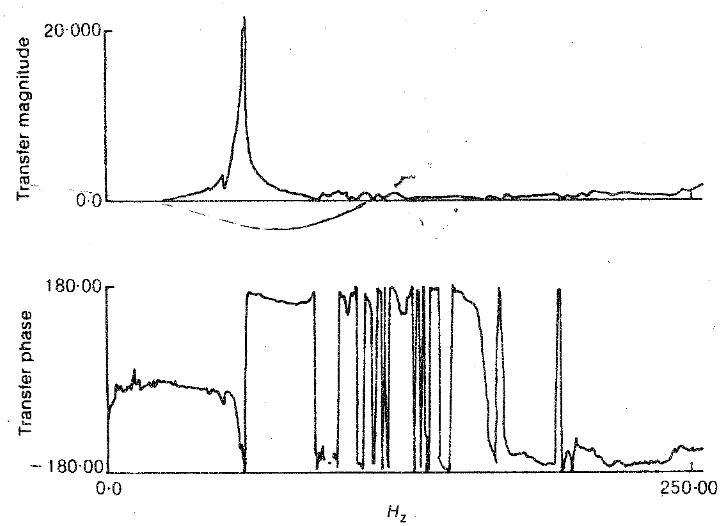


Fig. 5. Transfer function $\ddot{x}/F$ of a point at the top of the specimen

Table 1. *Comparison between analytical and experimental natural frequencies*

Frame mark	Frequency								
	f_1			f_2			f_3		
	Analysis	Experiment	Ratio	Analysis	Experiment	Ratio	Analysis	Experiment	Ratio
0	6·2	5·9	1·05	16·26	16·8	0·97	28·12	28·1	1·0
1	48·90	47·8	1·02	90·17	109·0	0·83	156·2	176·0	0·89
2	52·31	54·7	0·96	90·21	112·8	0·80	194·3	/	/

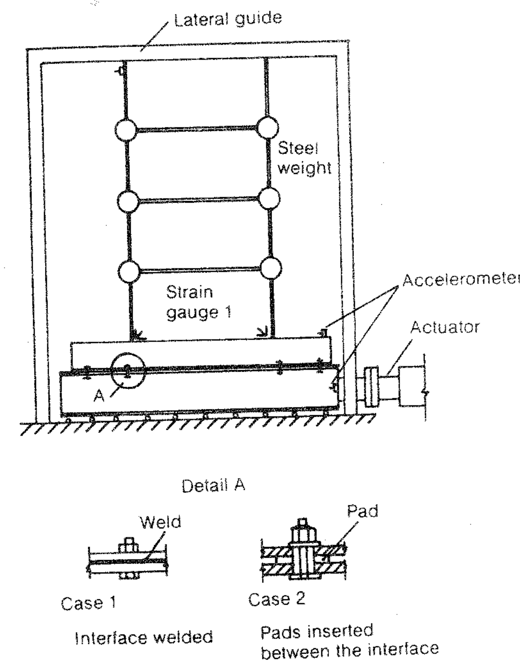


Fig. 6. Experimental arrangement for a frame on a sliding base

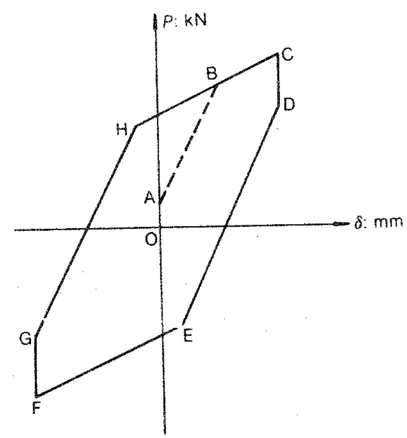


Fig. 7. Load–displacement curve of the sliding base

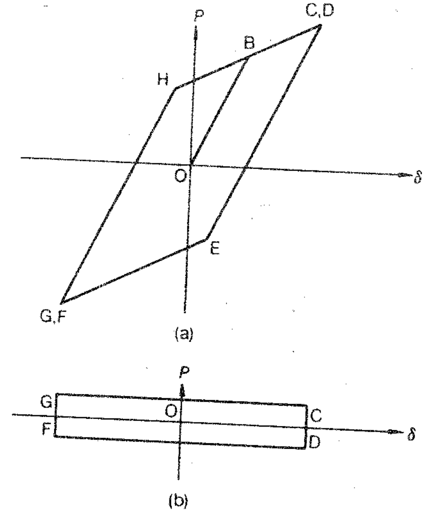


Fig. 8. (a) Bilinear hysteretic curve representing the behaviour of the base isolator; (b) rectangular hysteretic curve representing the frictional force

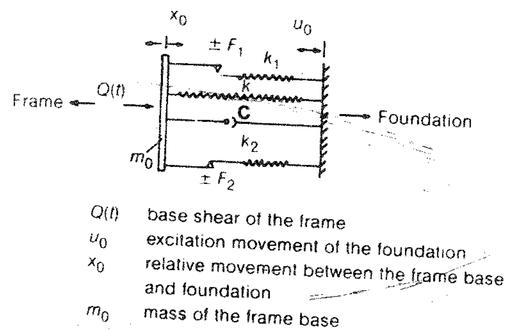


Fig. 9. Mechanical model of a sliding base

$$x_0 \doteq 0, \text{ or constant} \tag{3}$$

and $f(t)$ corresponds to lines OA, CD and FG in Fig. 7.

21. When the base excitation is increased, the base shear $Q(t)$ of the frame overcomes the frictional force $|F_1|$. Therefore, sliding occurs in the first frictional spring element

$$f(x_0, t) = F_1 \operatorname{sgn}(\dot{x}_0) + (k + k_2)x_0 + c\dot{x}_0 \tag{4}$$

This corresponds to the lines AB, DE and GH in Fig. 7.

22. When the base excitation is increased further, the base shear $Q(t)$ overcomes $|F_1 + F_2|$. Sliding then occurs in both frictional spring elements

$$f(x_0, t) = (F_1 + F_2) \operatorname{sgn}(\dot{x}_0) + kx_0 + c\dot{x}_0 \tag{5}$$

This corresponds to the lines HC and EF in Fig. 7.

23. Hence, $f(x_0, t)$ is a high non-linear function which depends on the magnitude of excitation and the process of loading and unloading, and equations (1) and (2) must be solved by a direct step-by-step integration program.

Influence of base sliding on response

24. To study the effect of base sliding on the response of the model, the model was bolted to a base constructed by a heavy steel box beam which was connected to a servo-controlled actuator, as shown in Fig. 6. The base holes were much larger than the bolts, so that the model could slide on the box beam when excitation was large enough to overcome the frictional force.

25. All the response signals were recorded using the instruments shown in Fig. 4. After this test, the base of the model was welded to the base box beam, and the tests were repeated. Because the model base and actuator were connected as a whole system, the real excitation of the base was a decay sine transient load, although the half sine impulse base excitations (with different amplitudes) were fed by the actuator to excite each model.

26. An accelerometer was fixed on the sliding table to record this transient excitation, which was then used to calculate the response of the infilled model. The comparison of calculated and measured results of strain response at point 1 (see Fig. 6) are shown in Fig. 10. When the model base was fixed, the strains in the

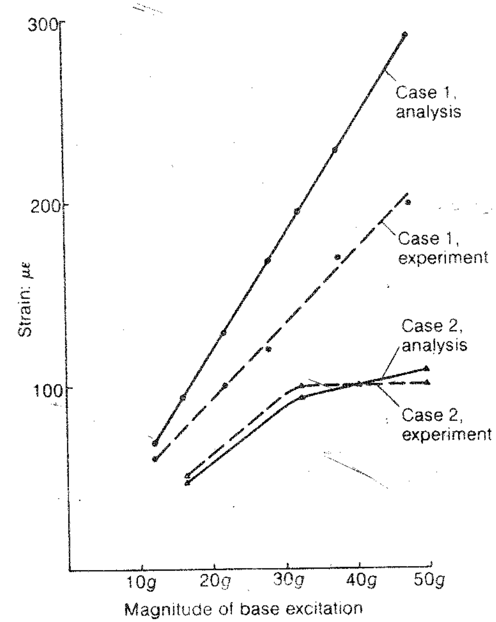


Fig. 10. Response on strain 1 due to transient base excitation

model increased with increase in the base excitation. When base sliding occurred, however, the strains were almost held constant in spite of the increase in base excitation. These results show convincingly the advantage of the sliding base, which can contain the effect of base excitation.

27. Figure 10 shows that in case 2 (sliding base), the discrepancies in the structural response between the analytical and experimental results were less than 11%, and during sliding the response magnitude of the structure did not change greatly although the excitation intensity increased. In case 1 (welded base), the analytical and experimental results show that the response magnitude of the structure grew linearly with the base excitation. In the latter case, the discrepancies between the analytical and experimental results became wider as the base excitation increased, reaching a maximum of 50% at an excitation of $50g$. The discrepancies in case 1 can be attributed to the fact that the welds at the base were not completely rigid, and these welds became more flexible with increased excitation, while a rigidly fixed base had been assumed in the analysis.

Response analysis of the infilled frame–sliding base system

28. To study the efficiency of a structure with a sliding base, equations (1) and (2) must be solved simultaneously with $f(x_0, t)$ defined by equations (3)–(5). These equations of motion of a complex structure with non-linear support can be solved by the ADINA program, provided that the sliding base is modelled by suitable elements. Three different truss elements are used to model the sliding base, as shown in Fig. 11. Strut 3 is a linear truss element, while struts 1 and 2 are non-linear truss elements having elastic-plastic characteristics, the von Mises yield criterion and kinematic hardening. Struts 1 and 2 display the same behaviour but have different cross-sections, different yield stresses and strain-hardening modulus. By suitably selecting the characteristics of these struts, the supporting stiffness of a sliding base having the same characteristics as that in Fig. 7 can be obtained. For example, let strut 2 be an ideal rigid-plastic material with magnitude OA (Fig. 7) representing its yielding force. Let strut 1 be a bilinear elastic-plastic material with modulus E, yield stress σ_y and strain hardening modulus E_T, the values of which are determined respectively by the slope of AB, the magnitude of AB and the slope of BC.

29. The response curves of the frame with three different groups of supporting struts are calculated as shown in Fig. 12. Curves σ_1 and u_1 show the response of an infilled frame with elastic supports, where the base movement is a minimum and the response stress of the frame is a maximum. Curves σ_2 and u_2 correspond to the

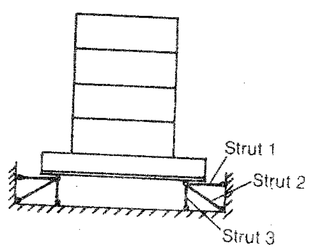
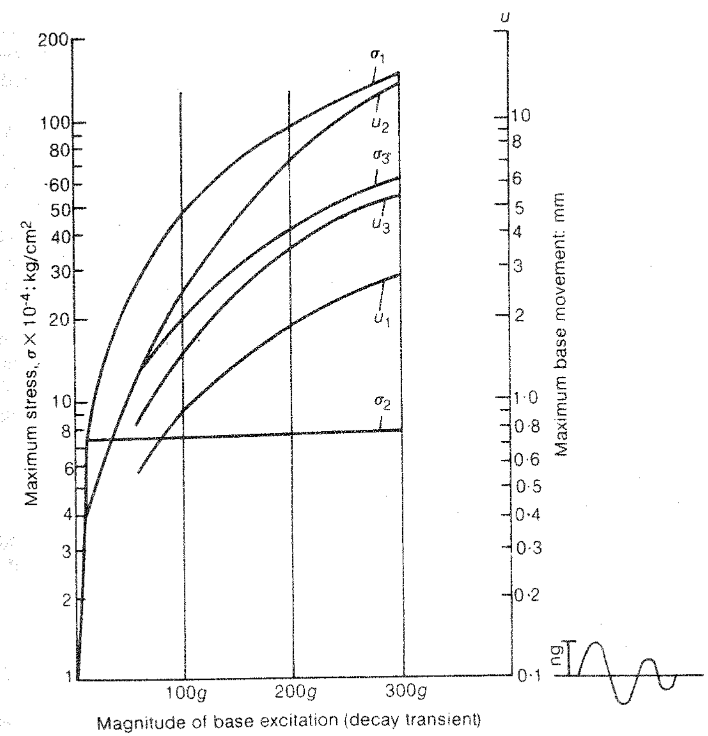


Fig. 11. Mathematical model of sliding supports

case in which both struts 1 and 2 are made of perfectly rigid-plastic material: when the base shear exceeds the yielding load of struts 1 and 2, the stress level reaches a constant value. In this case, the base movement is a maximum and the response stress is a minimum. Curves σ_3 and u_3 correspond to an intermediate case in which both struts 1 and 2 are made of elastic-plastic material.

30. Because the base movement and the response stress are a pair of contradictory values, a larger sliding displacement corresponds to a lower response of the frame. When it is safe for strength, it is poor for service. Therefore, a constraint must be applied in order to limit the sliding movement, and at the same time to suppress the response level to a minimum. It is important, therefore, suitably to adjust the location of points A, B, C and D in Fig. 7 so that an optimal design can be obtained.



σ maximum stress at corner of lowest infill (point 1 in Fig.6)
u maximum base movement
Suffix 1,2,3 denotes group number

Fig. 12. Response curves of a frame with different groups of supporting struts

Concluding remarks

31. Infilled panels can increase the strength and stiffness of a frame and improve the aseismatic capacity of a structure. However, the increased stiffness of the structure might induce greater earthquake loading. This difficulty can be resolved by incorporating a sliding base under the infilled frame. Such an infilled frame–sliding base system has, on the one hand, a high stiffness under normal loading conditions, and, on the other, reduces earthquake loading to the superstructure during strong earthquakes.

32. Because the base movement must be limited within an allowable range, the frame–base system must be analysed according to the service conditions of the structure. The substructure method has been presented in which the infilled frame as the upper substructure and the sliding base as the lower substructure are considered separately in the first instance. When the correct mathematical models for the dynamic characteristics of both substructures have been established through a procedure of analysis and/or experiment, the substructures are then coupled for response analysis.

33. The analytical procedure has been applied to one bare frame and two infilled frames. The calculated results of the natural frequencies of all three frames are in close agreement with the experimental results, the difference in first mode of vibration being only 2–5%.

34. The response of the infilled frames to base excitation has shown clearly the difference between the fixed base and the sliding base. In the case of the fixed base, the response of the structure increased linearly with increased magnitude of the base excitation. In the case of the sliding base, however, the response of the structure was deflected to approximately a constant magnitude when sliding occurred in spite of the base excitation being increased. This demonstrates the advantage of the sliding base over the fixed base in the case of strong ground excitation.

35. The solution procedure can be extended to analyse actual structures with different types of base isolator. In practical applications, further investigations are required on the behaviour of the particular base isolator, optimal matching of the structure to the base isolator, and the response analysis of the combined structure–base isolator system under random earthquake loading.

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