SEISMIC BEHAVIOUR OF COMPOSITE STRUCTURES

1. INTRODUCTION

Steel-concrete composite systems (also called mixed or hybrid systems) have seen widespread use in recent decades because of the benefits of combining the two construction materials. Reinforced concrete is inexpensive, massive, and stiff, while steel members are strong, lightweight, and easy to assemble. In decks, composite systems eliminate the need for formwork. In columns, two systems are commonly used, steel reinforced concrete (SRC), where a steel section is encased in concrete, and concrete filled tubes (CFTs). One important advantage of composite systems is that construction is accelerated through separation of trades. Initially, a bare steel frame is erected to carry the gravity, construction, and lateral loads during construction. As erection of the building progresses, concrete is cast in lower-level columns to form the composite system that will resist the total gravity and lateral loads (Griffis 1992).

Before starting with the assessment of the seismic performance of composite structures, it will be useful to understand the basic concepts of seismic design and performance. Since the probability of occurring a severe earthquake during the life of structures is usually low, seismic design is done using dual strategy (Clough and Penzien, 1993). This involves ensuring elastic response under moderate earthquakes and preventing collapse during a severe earthquake. While the former is taken care of the present Indian code (IS 1893 – 2002), there is at present no provision to check the latter. Therefore, it becomes the responsibility of engineers to give a thought and understand the performance of their structure during a severe earthquake.

Structures are likely to perform well under a severe earthquake if they are designed to be ductile. The property called "ductility" may be broadly defined as the ability to withstand large deformations without significant loss in strength (Fig. 1a). Another property, which contributes to good seismic performance, is the ability to dissipate energy by inelastic action under cyclic loading (Fig.1b). This energy is called

"hysteretic energy" and is given by the area enclosed within the load-deformation or moment-curvature diagram for a given cross-section. One way of increasing both ductility and energy dissipation capacity in members involving steel sections is to use higher thickness and thereby delay local buckling. However, this may not be always the economical solution as will be discussed later.

The total hysteretic energy dissipated by a structure is obviously the sum of the energies dissipated by various cross-sections, which have entered the inelastic range. Thus ensuring that as many cross-sections enter the inelastic range as possible before collapse can maximize the total energy dissipated. In other words, selection of a good collapse mechanism involving the formation of a large number of plastic hinges and avoiding concentration of inelastic action in just a few locations is the key to ensure good seismic performance. This technique is called capacity design (Paulay and Priestly, 1992).


(a)Ductile and Non-ductile behaviour

(b) Energy dissipation capacity
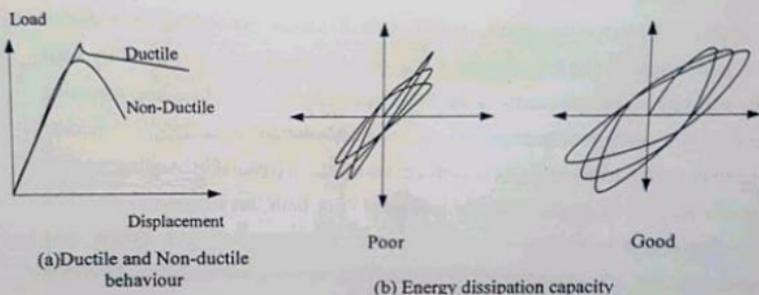
Fig.1 – Seismic Resistant Properties

2.0 SEISMIC BEHAVIOUR OF STRUCTURAL ELEMENTS

2.1 Slabs

Composite slab is meant by the system of casting a concrete slab over profiled steel sheeting. Normally, such slabs are designed for strength and their ductility is not considered. However in order to ensure failure by ductile yield line mechanism the following suggestions may be adopted. (i) use steel with a sufficiently long yield

plateau for the profiled sheeting, (ii) mechanical interlocks may be used to prevent shear bond failure. Sharp edged embossments are preferable over bluff embossments. (iii) fasten sheeting to supporting members to avoid falling off.

2.2 Beams

The primary objective of ensuring composite action between a steel beam and the overlying concrete slab is to obtain increased positive (sagging) bending moment capacity. Therefore, simply supported beams are widely used in composite structures rather than continuous beams or fixed beams as in moment resisting frames. However, continuous beams and moment resisting frames are not only more economical but also efficient seismic resistant systems due to their higher redundancies. As mentioned before, using thicker sections (compact sections) is likely to delay local buckling and improve the ductility and energy absorption capacity of beams. It should always be ensured that the full plastic moment M_p is attained before the collapse.

In case of simply supported beams, the formation of just one plastic hinge at mid-span leads to collapse. If the beam stiffness is low, it may reach the serviceability limit state well before the attainment of the full plastic moment M_p. Therefore, assuming that the serviceability state occurs at a mid-span deflection of (span/250), it would be prudent to limit the deflection, at the attainment of M_p, to (span/100). Another criteria that can be used to ensure a ductile behaviour is to limit the neutral axis depth at ultimate moment so that failure will take place by yielding of steel. Neutral axis depths less than 16% of total depth (beam plus slab) at ultimate moment are known to give adequate ductile behaviour.

Beams, which support composite slabs, might behave like over-reinforced concrete beams and their failure mode needs to be verified. The extra steel below in the form of profiled sheet lowers the neutral axis thereby resulting in a non-ductile composite section. Putting top steel will solve the problem but may be uneconomical. Therefore light and deep steel sections are preferable in such cases.

In the negative moment regions, which occur near the supports of fixed beams and continuous beams, there will be tension in the top, which may lead to cracking of the concrete slab. Putting reinforcement at the top as shown in Fig. 2 will ensure a ductile failure. This is further discussed in the context of partially restrained frames.

In capacity design of frames, strong-column weak-beam designs are usually preferred so that a mechanism of the type shown in Fig.3a is formed. If the beams are stronger than the columns, there is a likelihood of the formation of a soft-storey mechanism as shown in Fig.3b. With due regard to the uncertainties associated with predicting the material over-strengths, it is ensured that the plastic hinge is formed in the beam rather than in the column. This automatically ensures that the maximum possible energy is dissipated before collapse. Therefore, it is necessary to ensure that the composite action of the slab does not increase the strength of the beam leading to the formation of the plastic hinge in the column. This can be done by calculating the ultimate moment of resistance of the composite beam Mpb and verifying that (1.5 · times $M_{pb} < M_{pc}$). The factor 1.5 takes care of the worst condition wherein the beam strength may be more than ideal and the column strength may be less than ideal.
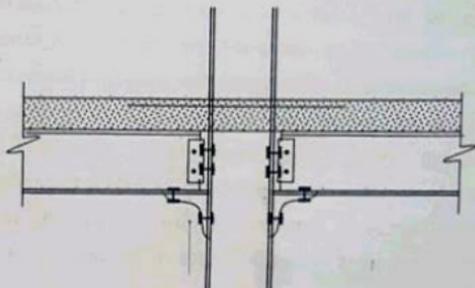

Fig.2 – Joint detail with slab reinforcement

(a) Preferred

(b) Avoidable
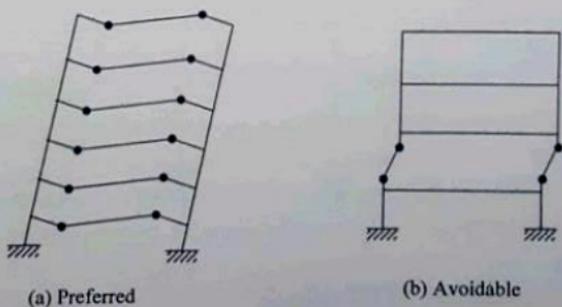
Fig.3 – Failure Mechanisms in Capacity Design

2.3 Columns

Composite columns may be classified into two groups: (i) concrete encased and (ii) concrete filled. In either case, the concrete may or may not be considered to be resisting gravity loads.

The primary reason for adopting concrete encased columns in buildings was to protect the steel section from fire. It should be realized that corrosion was not and is still not the primary reason behind encased columns in buildings.

Under the action of cyclic lateral loads arising from earthquakes, the concrete in encased columns can crack and spall leaving the steel section bare in the aftermath of an earthquake. To understand this phenomenon, let us consider a portal frame subjected to gravity loads as shown in Fig.4. Over a period of time, concrete in the columns would creep and shrink under the axial compressive load. Now if a lateral force H acts on the frame due to an earthquake, the compressive load on the left column will be reduced from P to (P-V). This reduction in the axial load would reduce the compressive strain in steel, which would tend to spring back inducing tension in the concrete. The amount of tension would depend on the magnitude of H and the span and height of the frame. However, it can be realized that the tension is bound to induce cracking and spalling of the concrete. Therefore, it is advisable to put some reinforcement, both longitudinal as well as transverse in the concrete to improve the seismic performance of the column.
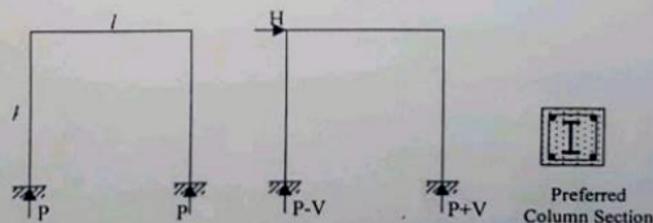

Fig.4 – Portal frame of composite members

Concrete filled tubular columns are becoming more and more popular due to several advantages. Apart from such factors as speed of construction, economy in formwork as well as ease of connections to steel beams, they offer superior seismic performance. By adopting thin-walled tubes, efficient utilization of the material is achieved in steel moment resisting frames and single columns such as bridge piers. The concrete inside being in a confined state offers excellent resistance to cyclic bending moments arising from earthquakes. In addition, in thin-walled polygonal sections, it prevents local buckling of the flange plates on the compression side thereby significantly increasing the strength, ductility and hysteretic energy dissipating capacity of the columns (Fig.5).
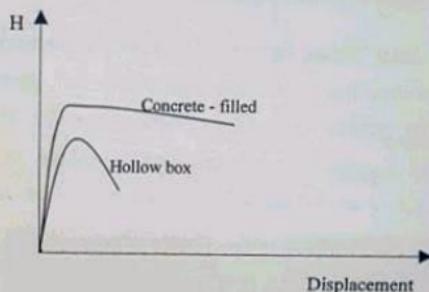

Fig.5 – Strength – displacement curve for hollow box and concrete-filled sections

3.0   SEISMIC BEHAVIOUR OF CONNECTIONS

One of the composite systems investigated, starting in 1989, is referred to as the RCS system. RCS composite systems resist seismic moments based on the connection between reinforced concrete columns and steel beams. Using RC rather than structural steel as columns can result in substantial savings in material cost and increase of the structural damping and lateral stiffness of the building. The two main categories in RCS connections to date can be characterized as the beam-through-type and the column-through-type. According to the literature, beams continuously passing through column panel zones (beam-through-type) behave in a ductile manner under seismic loading; however, orthogonal moment connection in the panel zone may be

labor intensive. Use of the column-through-type, using diaphragms or cover plates to connect the steel beam and column, may facilitate field construction; however, additional effort in connection details to ensure a better seismic capacity in terms of strength and ductility is needed.

The types of connections possible in composite construction are unlimited. Normally, connections in composite construction are designed disregarding the presence of the slab, as though they were just steel connections. A connection assumed to be simple might actually provide partial fixity due to the continuity of slab reinforcement. This could in turn transfer a considerable moment to the column top. Therefore the actual behaviour should be investigated and considered in the analysis. The connections should be able to resist both positive and negative moments and have a ductile failure.

The semi-rigid connection detail shown in Fig.2 has many advantages over conventional steel connections. Providing a few reinforcement bars over column lines not only improves the strength, ductility and stiffness of the connection, but also eliminates the top angle which is subjected to a combination of bending, axial and shear forces. However, it should be ensured that the reinforcement does not increase the moment carrying capacity of the beam leading to the failure of the column as explained earlier. Leon (1998) has suggested that the maximum reinforcement be less than that obtained by dividing the ultimate beam moment by the available lever arm. In addition, Leon has recommended the use of a strong seat angle.

One of the typical connection details is shown in Fig.6 [Chin-Tung Cheng and Cheng-Chih Chen (2005)]. Frames with simple connections will be incapable of resisting the lateral loads and so suitable lateral load resisting systems such as bracings need to be provided. Cyclic tests on composite connections have been carried out by Lee and Lu (1989) and Hajjar et.al (1998).

4.0 CONCLUSION

The properties of ductility and energy dissipation capacity were introduced and their importance in seismic resistance was pointed out. The behaviour of composite columns, slabs, beams and connections under seismic loading were described and methods of improving the seismic performance were suggested.
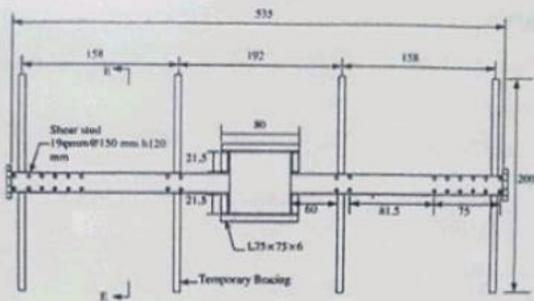
Distribution of shear studs
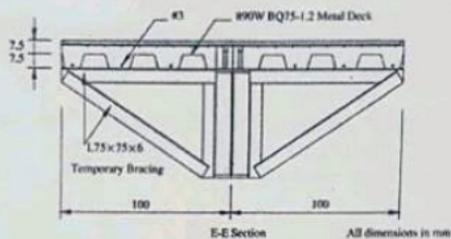
E-E Section

All dimensions in mm

Fig.6- Typical connection detail of specific beam column joint.
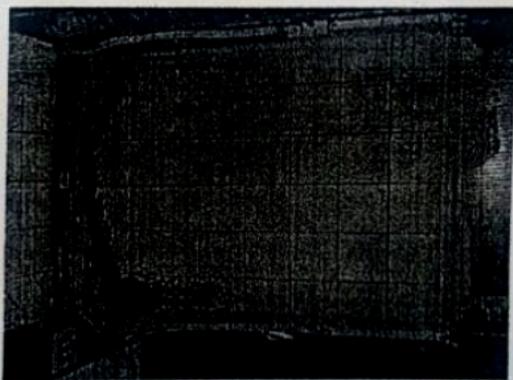
Fig.7 – One of the failure mechanism of the beam column joint.