Seismic Review of Conceptual Layouts in Earthquake Prone Areas: A Challenge for Practising Architects

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***Abstract*: -The poor seismic performance of the built environment during earthquakes highlights the necessity to design an infrastructure that is both strong and resilient. In this scenario, the architects need to play a critical role in every stages of a building project from conceiving to commissioning including the site selection, preparation of conceptual layouts, structural design, seismic detailing, construction and engineering of non-structural elements. A basic understanding of architectural aspects that govern the seismic behaviour of buildings is essential to ensure an earthquake resistant construction. The paper presents various aspects to be critically reviewed by architects in the preparation of earthquake resistant conceptual layouts. The configuration issues affecting the earthquake performance and their solutions are discussed. Finally, the importance in engineering and detailing of non-structural elements is highlighted.**

***Keywords:*- Earthquake, Conceptual layout, Seismic structural system, Shear wall, Soft storey, Non-structural elements.**

I. INTRODUCTION

A large part of India is prone to strong earthquakes with a huge risk of human lives and property. The 2001 Bhuj earthquake was an eye opener with significant damages to many modern multi-storey reinforced concrete frame buildings. The earthquake has resulted in a total tangible economic loss of Rs. 30,000 crores which is almost five times annual budget for Gujarat state [1]. Poor architectural configuration, inadequate structural design, improper detailing and poor construction practices were found to be the major concerns. Architects being important stakeholders of built environment, have a critical and responsible role in ensuring earthquake resistant construction. They occupy a key position in project conceptualization, planning and implementation. Poor conceptual design and detailing of various elements by the architect will seriously impair the ability of structural and construction engineers to incorporate earthquake resistance in buildings.

While structural safety is the main responsibility of engineers, the building form and configuration of earthquake resisting elements chosen by architects control the overall seismic behaviour of structures. A close coordination during conceptual stages between Architects and design engineers will ensure a good seismic design.

The architect shall have a basic understanding of various seismic resistant elements and the effect of their configuration, to arrive at a seismically optimized structural layout. Empowered with earthquake engineering, architects need to appraise their clients the importance of seismic design and the expected seismic performance of the building. A good quality construction documents and specifications along with their continuous monitoring & implementation are essential for a seismic resistant construction. The design and detailing of non-structural elements represents another important area where continuous interaction of architects with electrical, mechanical & HVAC engineers along with the product manufacturers are required to ensure its proper functioning under seismic shaking.

II. ARCHITECT'S ROLE IN SEISMIC SAFETY

As per the current practice, for most of the building construction projects in India, the architect leads a team of professionals including structural designers, contractors and other multi-disciplined engineers. The architect plays the major role in determining the building's shape, form, configuration, basic structural system, materials, non-structural systems and components. It is important that the decisions and the input provided by the architect, governs to a very large extent the building's success or failure under seismic conditions. The non-structural components and systems alone have caused damage more than 70% of the buildings total value in past earthquakes around the world. Accordingly, architects need to be fully involved in the seism design of these components to avoid life loss/injury in future earthquakes.

Continuous interaction between architects and contractors throughout the project ensure that detailed documents and drawings are provided for execution and they are familiar with various aspects of earthquake design detailing. Site meetings shall be arranged with contractors and sub-contractors as and when required along with the structural engineers to discuss various details provided in the documents and provide more clarity to the method of construction. Structural materials should be of high quality and workmanship up to required standards. An architect should impress upon the client the need for good quality control during construction. In case of deviations, proper remedial actions shall be suitably identified. It is also important that architects learn new methods of construction and detailing from experienced and skilled contractors involved in their project to empower them in future projects.

III. COLLABORATION BETWEEN ARCHITECTS AND DESIGN TEAM MEMBERS

Building construction projects require a good understanding, and a team work of various professionals including but not limited to architects, structural designers, mechanical services engineer, project managers & contractors. The key to successful interdisciplinary collaboration is in understanding that it is not a technology but rather a psychology [3]. Architect Christopher Arnold [4] recommends that collaboration must occur before architectural concepts are developed or very early on in their conception.

In the design of a seismic resistant building, collaboration between architects and structural engineers is really challenging considering that they work on different objectives to meet the client requirements. While architects focus on functional and aesthetic requirements, engineers work with an objective of producing an efficient structural design complying various local code requirements. During preliminary engineering of any building project, the architect playing the lead role shall discuss with design engineers various key issues in structural design and possible geotechnical challenges. Decisions taken at this level will help in formulating guidelines for detailed engineering and advanced collaboration in later stages.

IV. BASIC SEISMIC STRUCTURAL SYSTEMS

Architects in collaboration with structural engineers shall investigate the various seismic structural systems that match best with the conceptual layout. The system includes both the vertical and horizontal resisting elements that ensure a continuous load path from top to the foundation levels. The framing system must be chosen at an early stage in the design because the different system characteristics have a considerable effect on the architectural design. FEMA 454[5] provides a detailed description of various seismic structural systems for use in conceptual layouts. A brief review of basic seismic structural systems is provided to enable the architect to select the best in the conceptual layout.

A. Vertical Lateral Resistance system

The architects have the choice of different types of vertical lateral resistance system which must be finalized at the beginning of the conceptual layout based on function and aesthetics. In some cases, a mix of the various systems using one type in one direction and another type in the other can be used. The *moment resistant frame* shown in Fig. 1 consists of a grid of vertical columns and horizontal beams members. The earthquake imposed lateral forces are resisted primarily in flexure by beams and columns mobilized by strong joints between them. These frames provide the most architectural design freedom due to the space availability in the absence of diagonal bracings.

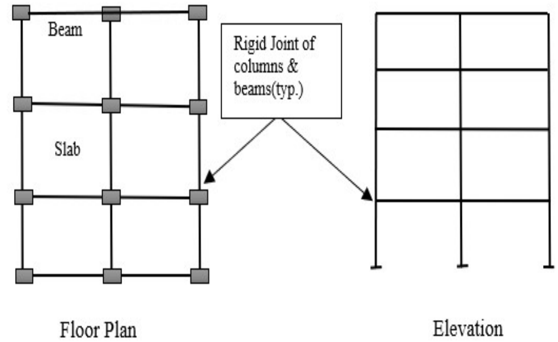

Fig. 1 Moment Resistant Frames

Braced frames receive the lateral load from horizontal diaphragm elements transferring finally to the foundation. Compared to the shear walls, they provide better ductility and more architectural freedom. Braces help in reducing overall lateral displacement of buildings, and bending moment demands on beams and columns. The braced frames can be broadly classified into concentric and eccentric frames. In the case of concentric braced frames, the centrelines of bracing members meet the horizontal beam member at a single point where as in eccentric braced frames, the bracings are deliberately designed to meet the horizontal beam some distance apart from one another. The beam member between the bracing ends known as a link beam provide required ductility to dissipate the earthquake energy. The braced frame system is shown in Fig. 2.

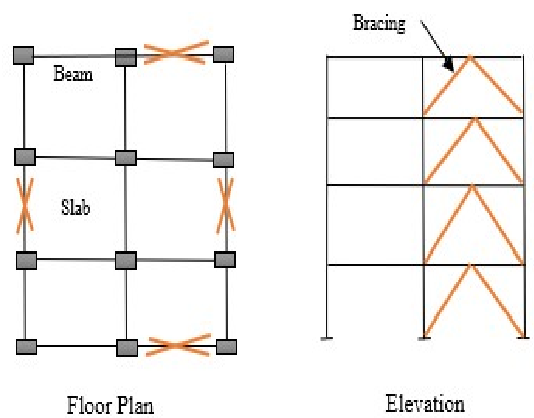

Fig. 2 Braced Frames

Shear walls shown in Fig. 3 are designed to receive lateral forces from diaphragms and transmit them to the ground. The forces in these walls are predominantly shear forces. To be effective, shear walls must run from the top of the building to the foundation with no offsets and a minimum of openings. They are normally introduced with a requirement to reduce the lateral displacement of the structure. Shear walls are more effective when placed along the periphery of the building.

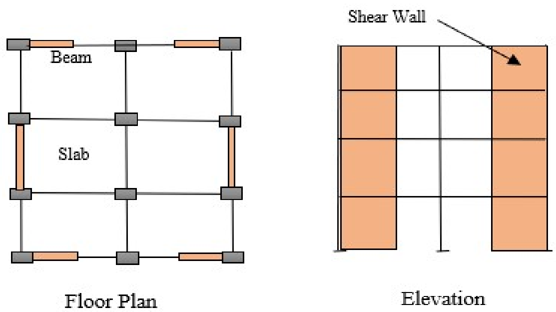

Fig. 3Shear Walls

For tall buildings, use of braced frames and shear walls alone may not be sufficient to control their overall lateral displacement as well as the force demands on various structural members. In such cases, more rigid structural systems like *Tube, Tube-in-Tube and Bundled Tube* systems are used. The *Tube System* shown in Fig. 4consists of one perimeter tube of closely spaced heavy columns interconnected with beams along with a central core of heavy reinforced concrete walls. In the case of *Tube-in-Tube System,* a second tube of columns interconnected with beams is created inside the perimeter tube. When a *Tube-in-Tube System* fails to control the lateral deformation of the building a *Bundled-Tube system* consisting of a set of tube systems stacked together can be used. The closely-spaced columns of the different tubes are placed in line to form an overall tube system.

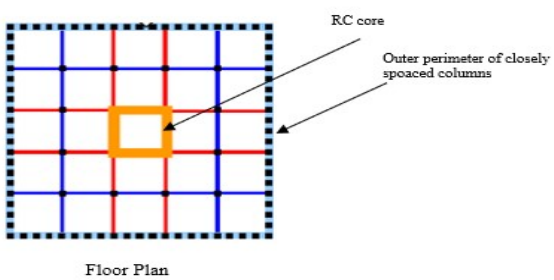

Fig. 4Tube Systems for Tall Buildings

B. *Horizontal Lateral Resistance system*

The horizontal resistance members normally knowns as d*iaphragms* are used to transfer the earthquake lateral loads generated at different floor levels to vertical lateral resistance system. The diaphragms are normally provided by floor and roof slabs of the structure and constitute an important element of earthquake resistant system.In some cases, additional horizontal bracing systems are introduced to act as diaphragms. Depending upon the area and material of construction, a diaphragm may be either flexible or rigid. In the case of flexible diaphragms, the lateral forces are distributed to various members in proportion to tributary areas they support whereas for rigid diaphragms the forces are distributed in proportion to the stiffness of vertical resistant systems. It shall be noted that the penetrations caused by staircases, lifts etc. in the floor slabs affect the performance of diaphragm elements at these locations.

V. CONFIGURATION PROBLEMS AND SEISMIC ISSUES

Having selected the proper earthquake resistant elements, the next step would be their arrangement at different floor levels. At this stage architects shall be aware of the potential problems originating from configuration issues and suggest possible solutions in collaboration with structural engineers. An intelligent configuration would eliminate the problems that would crop up in the project in future.

A good seismic performance of a building requires that it consists of a robust layout of earthquake resisting elements with adequate lateral strength, stiffness and ductility. The architect shall therefore ensure that the building is seismically optimized in its configuration and demonstrates the best arrangement of its seismic resisting elements in complete harmony with the architecture. The buildings that deviate from simple regular geometry with nonuniform mass and stiffness distribution resulting in stress concentration and torsion are said to be irregular. A good collaboration between architect and structural engineers eliminates or at least minimizes the irregularities. The great earthquake engineer, Late Henry Degenkolb [6] was emphatic in stressing the importance of configuration on seismic design and quotes “If we have a poor configuration to start with, all the engineer can do is to provide a band-aid to improve a basically poor solution as best he can. Conversely, if we start off with a good configuration and a reasonable framing scheme, even a poor engineer can’t harm its ultimate performance too much”. A detailed study of irregular buildings with plan & vertical irregularities is reported in [7]. Some of the serious configuration conditions that originate in the architectural design and have the potential to seriously impact the seismic performance are briefly reviewed below.

A. *Soft and Weak Storeys*

A soft storey is the one whose lateral stiffness is less than that of the storey above whereas a weak storey is identified as the one whose lateral strength is less than that of the storey above[2]. A soft or weak storey at any height though creates a problem, the serious conditions occur when such features are present near the base of building due to larger lateral loads transferred at this level. The soft first storey failure mechanism is shown in Fig.5. It can be seen that with a soft storey, almost

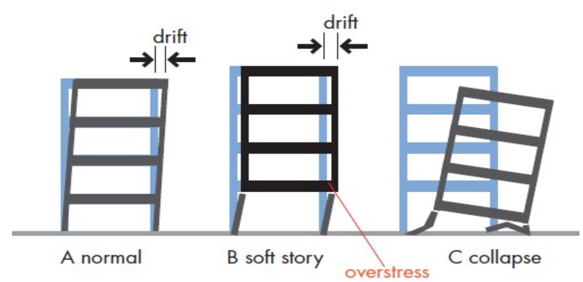

Fig. 5 Typical Soft First Storey Mechanism

all the drift occurs in the first floor causing the stress concentration leading to the collapse. A soft first storey may be created due to many conditions such as ground floor columns significantly taller than those above, some column members being terminated at first floor to increase the openness and finally an open ground floor that supports heavy structural or non-structural elements above. Some solutions to the soft first storey include the addition of columns or stiff elements such as shear walls or bracings in the ground floor.

B. Short Column Effects

Reinforced concrete frames that have columns of different heights within one storey requires special attention during conceptual design by architect and later detailing by the structural designer. These are typical of buildings on sloping ground or those with mezzanine floors as shown in Fig. 6. A special case of short columns arises when an RC or masonry wall is constructed for a partial height along the column to accommodate windows or basement ventilation. In such cases, a short column attract much larger earthquake force due to its higher stiffness and suffers damage during earthquakes. Where short column effects cannot be avoided, special detailing practices as envisaged in IS:13920[8] shall be followed.

C. Variations in Perimeter Strength and Stiffness

A building with wide variation in the perimeter strength and stiffness will be subjected to torsion as the center of mass in this case will not coincide with the center of resistance. A common instance of an unbalanced perimeter is that of open-front design in buildings such as large department stores and shopping malls. The possible solution to this type of problem is to arrive at a uniform perimeter resistance by the provision of additional shear walls or moment frames at the open front.

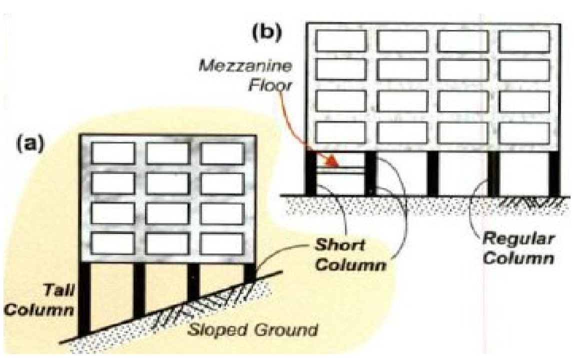

Fig. 6 Building with Short Columns

D. Re-entrant Corners

The re-entrant corner is the common characteristic of building configurations that assumes in plan, the shape of an L,T,U,H or a combination of these shapes. This is a most useful set of building shapes, which enable large plan areas to be accommodated in relatively compact form. However, these configurations represent one of the most difficult problem areas in seismic design. There are two problems associated with these configurations. The first is that they tend to produce differential motions between different wings of the building due to stiffness variations resulting in local stress concentrations at the re-entrant corner. The second problem is torsion developed due to the center of mass not coinciding with the center of stiffness. A building is said to have a re-entrant corner in any plan direction, when its structural configuration in plan has a projection of size greater than 15 percent of its overall plan dimension in that direction[2]. A typical case of torsion in an L-shaped building is shown in Fig. 7. The problem of re-entrant-corners in various configurations can be solved either by separating structurally the building into simpler shapes or tying the building together more strongly with elements positioned to provide a more balanced resistance .

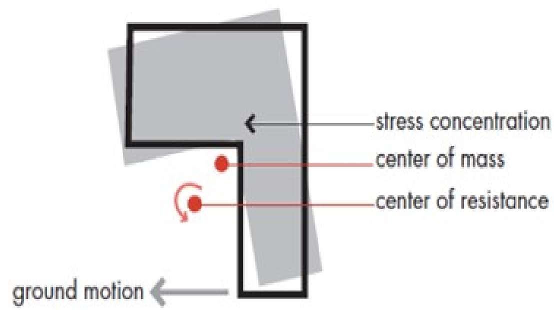

Fig. 7 Torsion in an L-Shaped Building

VI. NON-STRUCTURAL ELEMENTS

Non-structural elements represent those parts of buildings which are not intended to resist earthquake loads applied to the primary structure and include exterior walls, internal partitions, cladding panels, stairways, suspended ceilings, equipment items and various building services. These elements transform a structure into a habitable and functional building. Non-structural elements have the potential to modify earthquake response of the primary structure in an unplanned way leading to severe structural damage or even collapse. Evidence from earthquakes around the world shows that non-structural damage typically represents the greatest monetary loss in an earthquake. Architects shall therefore consult engineers(mechanical, electrical, HVAC) at an early stage in their design to ensure that non-structural elements perform adequately during earthquakes.

The two seismic aspects that contribute to non-structural damage are acceleration and inter-storey drift. During a seismic event, the building amplifies the ground accelerations; the amplification being larger at higher levels. It shall be ensured that non-structural elements have enough strength to resist their own inertia forces induced by such accelerations and are attached to structural members to prevent the damages. The inter-storey drift defined as relative horizontal movement between floors is an important aspect to be looked into as they can damage non- structural elements connected to both floors. Careful separation of non-structural elements from the structure can avoid the damage A detailed review of various types of non-structural elements and their connection details is available in [5,9]. Based on their damage potentials, the non-structural elements are briefed below under three types; infill walls, staircases and others including partition walls, cladding, curtain walls, parapets, suspended ceilings, raised floors, mechanical & electrical equipment.

A. Infill Walls

Infill walls are non-structural walls constructed between columns. In an earthquake event, infill walls can cause serious structural damage to a building and therefore require careful considerations in obtaining appropriate solutions. To be considered as non-structural, infill walls must be constructed and connected so that they are not capable of altering the intended structural behaviour to a significant degree. The problems associated with the use of infill walls is broadly two-fold. Firstly, their use stiffens a building leading to increased accelerations & inertia forces thereby increasing the likelihood of damage to structural and non-structural components. Secondly, an infill wall prevents a structural frame from freely deflecting sideways damaging itself and surrounding frame. The infill walls act like sacrificial fuses in buildings developing cracks under severe ground shaking but help share the load of the beams and columns until cracking. The reversed cycles of earthquake loading will finally cause diagonal cracks in infill walls as shown in Fig. 8. A heavily cracked infill is highly vulnerable to out-of-plane forces and pause a potential hazard to people unless adequately restrained.

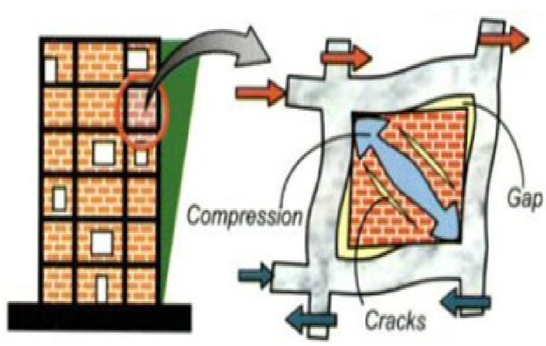

Fig. 8Infill Walls and Columns under Earthquake

A solution to problems associated with infill walls is to provide a very stiff primary structure such as reinforced concrete (RC) shear walls. In this case the less stiff infill walls do not attract horizontal forces. The most common solution used in many seismically active countries is to provide a separation gap between infill panels and structural frame. Separation gaps allow the frame to deflect freely without being impeded by the wall. Normally a vertical gap of 20-80 mm wide is provided between columns & the wall and a horizontal gap of 25mm is provided between the top of wall and the soffit of the beam above.

B. Staircases

Unless stairwell partitions are designed to provide shear resistance, the stair flights and their enclosing partitions are usually non-structural. Where staircases are strongly attached to the structure, they can attract high levels of seismic force due to their diagonal braces arrangement as shown in Fig. 9 damaging themselves and the primary structures. If stairs are severely damaged, building occupants may be unable to exit a building after an earthquake. To avoid damage to both staircase and structure, the recommended solution is to separate the stairs by providing a sliding joint at each floor.

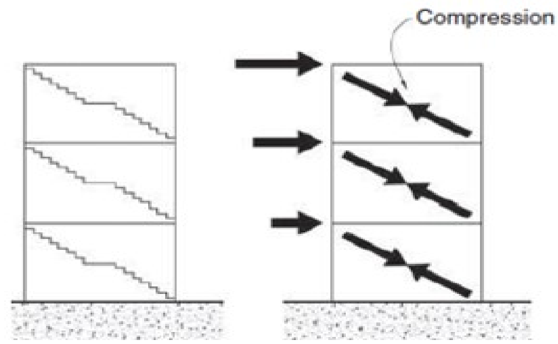

Fig. 9 Bracing Action of Stairs Connected to the Structure

C. Other Non-structural Elements

These elements include those that do not damage the structural elements but which require adequate connection with structure to minimize their damaging potential. The items discussed include partition walls, cladding, curtain walls, parapets, suspended ceilings, raised floors, mechanical & electrical equipment. *Cladding* refers to the non-structural external walls. They can be put under three main categories as masonry, panels and other materials. Though they are not infill walls, they must be separated from the main structure by the method of separation to minimize the undesirable seismic effects. Cladding where provided in the form of panels consists in many cases precast concrete panels and represent a serious hazard should they fall from a building. The cladding panels shall permit the movement of main structural frames without offering any resistance. A typical arrangement consists of a fully separated storey height panel supported at its top and provided with a gap at bottom to allow inter-storey drifts as shown in Fig. 10.

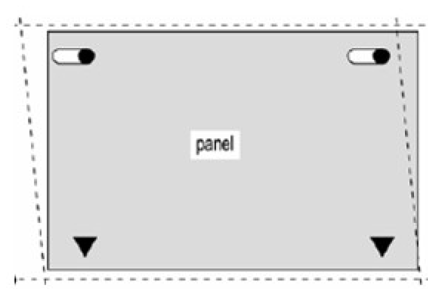

Fig. 10 Movement of Panel Relative to Structure

In the case of windows and *curtain walls*, earthquake-induced inter-storey drifts damage thin and brittle panes of glasses and cause injuries. For windows, although a small clearance provided around all four sides of a glass pane is sufficient under small deformations, specially designed *seismic mullions* shall be considered in case of large movements. For curtain walls, the approach is to isolate glass panes from their frames by providing movement clearances.

Partitions can be either rigid when constructed in concrete and masonry or of lightweight construction. In case of rigid partitions, they need to be separated from the building frame. The rigid partitions are to be anchored at top and bottom for lateral support and provided with separation details to allow storey drifts. The light weight partitions also require separation from primary structure, if the anticipated inter-storey drift exceed the limits for the partition material. Due consideration shall be provided to maintain acoustic privacy and fire ratings.

Suspended ceilings and raised floors represent a non-structural group which can cause injuries to occupants, disruption of services and financial losses in case of earthquake events. A suspended ceiling consists of a grillage of light metal members hung from fine wires supporting ceiling tiles. Suspended ceilings, including the light-fixtures shall be braced to prevent their uncontrolled swinging and consequent damages. A typical arrangement of suspended ceiling bracing is shown in Fig. 11. In case of raised floors, resistance to horizontal accelerations is achieved through seismic restraint around the floor perimeter and vertical supports. Architects rely on a combination of manufacturers information and structural engineering advice to specify a system for suspended ceilings and raised floors.

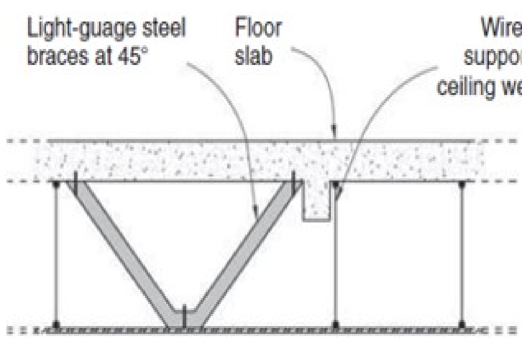

Fig. 11Suspended Ceiling Bracing

VII. CONCLUSIONS

The seismic resistance of buildings is a critical issue to be addressed by architects by taking it as an integral part of architectural design. The required technical expertise to achieve this objective shall be provided by structural engineers and through close collaboration with other specialists. The requirement of early collaborations and role of architects in ensuring the seismic safety are highlighted. The paper provides some basic understanding to practicing architects on seismic structural system, configuration issues and their solutions. The importance of non-structural elements and their connections are also discussed.

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