Earthquake Safe Koti Banal Architecture
of
Uttarakhand, India

Disaster Mitigation and Management Centre

Department of Disaster Management

Government of Uttarakhand, Uttarakhand Secretariat

Rajpur Road, Dehradun – 248 001

Uttarakhand (India)

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Preface

Geodynamic evolutionary history and ongoing tectonic activities together render the Himalayan terrain highly vulnerable to a number of disasters. Increasing anthropogenic intervention in the geo-environmentally fragile terrain and enhanced population pressure have added to the devastating potential of the disasters but these would have always been a cause of concern for the people inhabiting this terrain who would often have witnessed the fury of earthquakes as well. Accepting the challenge put forth by nature these population groups attempted ways of protecting their interests from the wrath of nature and human survival in this hostile terrain testifies this fact.

Earthquake vulnerability of the region could not deter construction of multistoried houses and people experimented with locally available building material and evolved an architectural style unique to the terrain. This style exhibits structural evolution trends whereby stone masonry is judiciously used with abundantly available wood to provide appropriate strength and flexibility to the structure. These structures have survived many earthquakes and lack of the elements of earthquake safety would have razed these to ground.

This study has been carried out in Rajgarhi area of Uttarkashi district of Uttarakhand that has a number of magnificent traditional multistoried structures and is an attempt to investigate the elements of seismic safety in these. It shows that the people in this region had evolved an elaborate methodology for detailing of earthquake safe structure around 1,000 years before present times and this represents a distinct architectural style (Koti Banal) of the area. There is however pressing need to protect these structures that are being put to disuse and are deteriorating fast due to the lack of maintenance.

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The ideas expressed in the report are those of the authors and do not necessarily reflect official policies of the Department of Disaster Management, Government of Uttarakhand or Disaster Mitigation and Management Centre.

10.06.2007
Disaster Mitigation and Management Centre
Uttarakhand Secretariat, Dehradun

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Executive Summary

Despite being located in earthquake sensitive region and often experiencing seismic tremors the State of Uttarakhand exhibits elaborate tradition of constructing multistoried houses. Both the local dialects of the State (Kumaoni and Garhwali) have unique words for identifying four different floors of a building. This is suggestive of common occurrence of multistoried structures in the region.

Rajgarhi area of Uttarkashi district has a large number of intact multistoried traditional houses that exhibit marked antiquity and distinct construction style. Detailed investigations were undertaken in this area to establish the antiquity of the traditional structures, as also earthquake safety provisions incorporated traditionally in these.

Investigations suggest that the region had evolved a distinct, elaborate and magnificent earthquake safe construction style as early as 1,000 years before present. This distinct construction form is designated Koti Banal architecture. This architectural style exhibits existence of elaborate procedure for site selection, preparing the platform for raising the multistoried structure, as also for the detailing of the entire structure that was constructed on principles somewhat akin to that of framed structures of modern times.

Locally and then abundantly available building material (wood and stone) was judiciously used in these structures and the structural designing of the structures suggests that the ones responsible for designing these buildings had fairly good idea of the forces likely to act upon the structure during an earthquake.

The significant components of Koti Banal architectural are:

- i) Simple layout of the structure,
- ii) Construction on elaborate, solid and raised platform,
- iii) Judicious use of locally available building material,
- iv) Incorporation of wooden beams all through the height of the building at regular intervals,
- v) Small openings and
- vi) Shear walls.

Koti Banal architecture was however highly utilitarian and did not cater to the comfort of the inhabitants that is responsible for these houses being put to disuse presently. Evidences suggest that aberrations to the original construction style had started to creep in as early as 728 ± 60 years before present.

The representative structures of this architecture are observed to be deteriorating fast for the lack of patronage, resources and awareness amongst the masses regarding their significance. It is therefore suggested that these structures be conserved as heritage structures of the State. This effort of the State would provide the coming generations with an opportunity to have a glimpse of the magnificent architectural tradition of the region while the researchers would be provided with an opportunity of studying this majestic architectural tradition of Uttarakhand.

There also exists possibility of promoting ecotourism in the region by launching a well designed strategy woven around these traditional structures. Success of this strategy would ensure maintenance and upkeep of these structures.

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The Hazard Prone Terrain

Plate tectonics is presently recognized to be the main cause of seismic tremors. Subduction of the Indian Plate beneath the Eurasian Plate and its consequent collision with the same after the consumption of the intervening oceanic crust resulted in the evolution of the Himalayan mountain belt. The continent – continent collision caused uplift, deformation, dislocation and metamorphism of the intervening sediments. These have rendered the terrain highly fragile and prone to mass wastage. The north – northeastward drift of the Indian Plate has not yet seized; ongoing built up and release of strain due to this movement is responsible for frequent seismic tremors in the region.

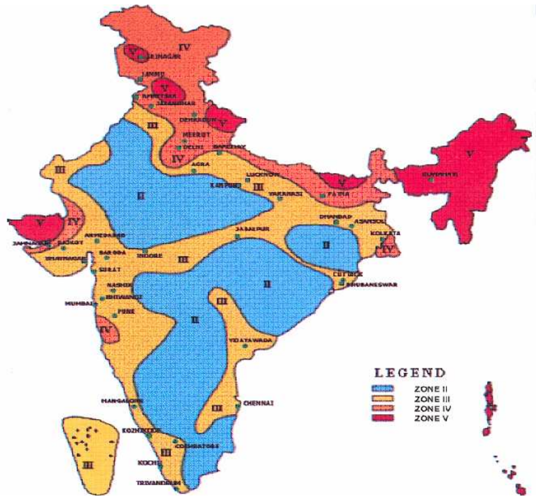

Fig. 1: Earthquake damage risk map of India.

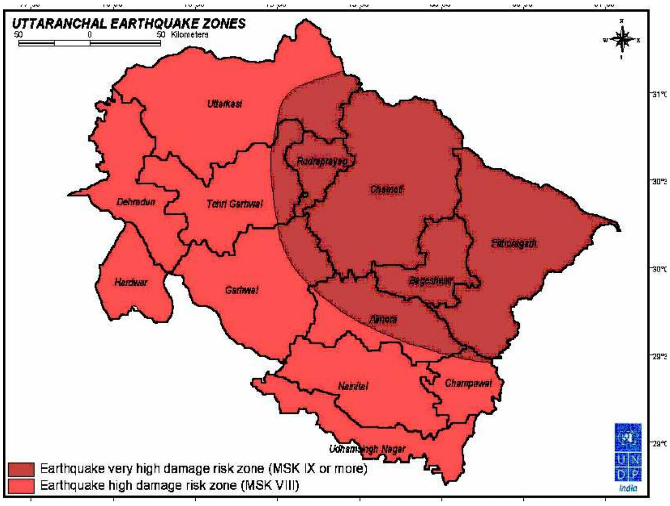

Fig. 2: Earthquake damage risk map of Uttarakhand.

Entire Himalayan terrain is recognized as being highly vulnerable to earthquakes[1,2] and in the past the region has been jolted by four Great Earthquakes (Magnitude > 8 on Richter Scale); 1897 Shillong Earthquake, 1905 Kangara Earthquake, 1934 Bihar - Nepal Earthquake and 1950 Assam Earthquake apart from Kumaun Earthquake of 1720 and Garhwal Earthquake of 1803[3]. Regions between the rupture zones of the Great Earthquakes are recognised as seismic gaps that are interpreted to have accumulated potential slip for generating future Great Earthquakes. Entire State of Uttarakhand falls in the seismic gap of 1934 Bihar - Nepal Earthquake and 1905 Kangara Earthquake and is categorized as falling in Zone IV and V of the Earthquake Risk Map of India (Fig. 1 and 2). This region has been identified as a potential site for a future catastrophic earthquake[1]. The region has also witnessed seismic events of lesser magnitude (1991 Uttarkashi Earthquake, 1999 Chamoli Earthquake).

Unplanned growth, concentration of population and infrastructure, negligence of construction norms, abrupt change in construction material without appropriate technical interventions and lack of awareness as also trained manpower have together resulted in enhanced seismic vulnerability of the Himalayan region.

[1] Bilham, R., Gaur, V.K. and Molnar, P., 2001, Himalayan Seismic Hazard, Science, 293, 1442-1444.

[2] Feldl, N. and Bilham, R., 2006, Great Himalayan earthquakes and the Tibetan plateau, Nature, 444 (9), 165 – 170.

[3] Thakur, V.C., 2006, Seismotectonics and earthquake geology aspects of Northwestern Himalaya, Geological Survey of India Special Publication, 85, 61-71.

Earthquake Safety and Traditional Construction Practices

Human response to emerging exigencies has resulted in fine tuning of resource management practices as also life support strategy, so as to protect the interests of the human communities. Based upon experience, experimentation, accumulated knowledge and ingenuity human populations around the globe have evolved innovative practices for ensuring survival against all odds. Disasters are not a new phenomenon for human race and ever since its appearance on the planet human race has been successfully devising ways of overcoming the challenge put forth by disasters. Survival and supremacy of the relatively unspecialized species testifies this fact.

Communities residing in areas often affected by earthquakes were quick to understand the fundamental premise of earthquake safety that indicates possibility of avoiding loss of human lives in a seismogenic event by ensuring safety of the structures. This fundamental understanding led to the evolution of innovative practices for minimizing human losses emanating from structural collapse. Dhajji –dewari and Taq are the famous indigenous construction styles of Kashmir. Both these utilize locally available stone and timber in a particular manner to achieve desired levels of seismic safety in the structures. Quetta bond is an often quoted example of human quest to reduce earthquake induced losses.

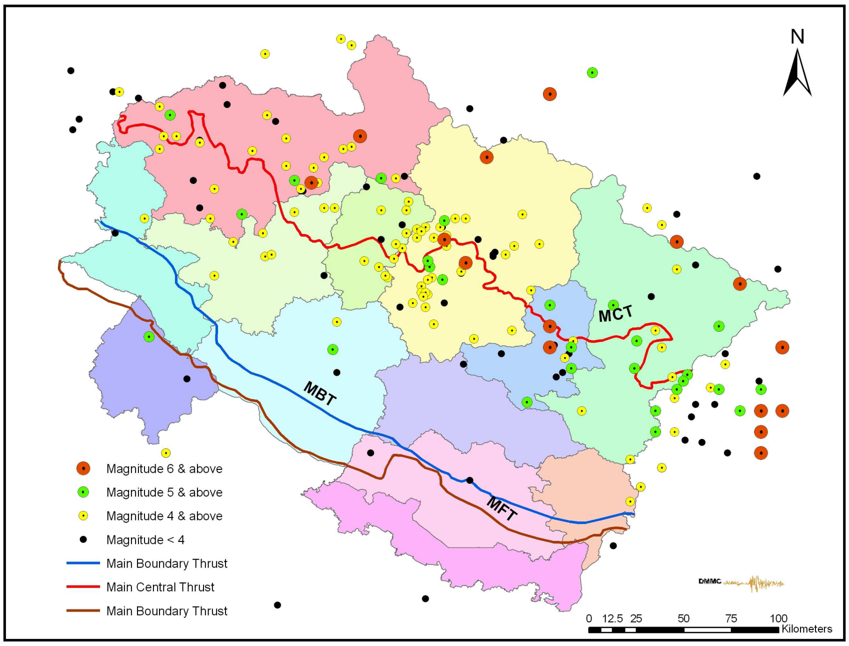

Fig. 3: Map showing epicenters of earthquakes in Uttarakhand.

The State of Uttarakhand falls in seismically highly sensitive zone. Though the region has been spared by high magnitude earthquakes (M > 8 on Richter Scale) for quite some time this might not have been the case all through. The region has witnessed devastating earthquakes in 1720 (Kumaun Earthquake) and 1803 (Garhwal Earthquake). In the recent past the region has witnessed earthquakes in Uttarkashi (1991) and Chamoli (1999) and the seismic activities in the region suggest (Fig. 3) that earthquakes would have been a common feature in the past as well. Despite often experiencing earthquakes (*Chalak* in Kumaoni; the local parlance) multistoried houses are common in Uttarakhand and apart from the cattle sheds one can hardly locate a single storied traditional house in the region.

The zeal to protect the community, by utilizing accumulated knowledge and experimenting with locally available building material, paved way for the evolution of a unique architectural style that exhibits structural evolution trends whereby dry stone masonry, as also stone – lime / mud / clay mortar masonry was judiciously used with abundantly available wood to provide appropriate strength and flexibility to the structures.

Despite threat of earthquakes looming large, multistoried houses are in vogue in the region. It would not be easy for one to locate a single storied traditional house in the region even today, except for cattle shed (*channi* in Kumaoni; the local parlance). There exist unique words for identifying as many as four different floors in the two local dialects of the region; Kumaoni (ground floor, *goth*; first floor, *chaak*; second floor, *paan*; third floor, *chaj*) and Garhwali (ground floor, *kholi*; first floor, *manjua*; second floor, *baund*; third floor, *baraur*). Unless often required a unique term cannot be introduced in any language. This clearly point towards common occurrence of multistoried houses in the region.

In Yamuna and Bhagirathi valleys of the Garhwal region four to five storied traditional structures can still be observed (identified as *Chaukhat*; four storied or *Panchapura*; five storied). These age old structures must have witnessed many earthquakes. In the absence of the elements of earthquake safety these would have long been razed to ground.

Cement based construction practices are fast getting popular in the entire State even though it is not suited to the climatic conditions of the region. High social status attached to the new type of construction together with increasing difficulty in mustering traditional building material (stone and wood) have contributed to its popularity. As has been indicated in studies[4] carried out in the region the masons switching over to cement based construction practices are not technically competent and are adding to the seismic vulnerability of the region. With masses loosing interest in the traditional construction elements of local architecture are being lost; lack of patronage is forcing the traditional masons to switch over to new construction practices. Structural details, as also architectural and utilitarian aspects of the traditional structures have not so far been studied and postponing this could be too late to document these.

As has been stated above, survival of the traditional structures over generations in the earthquake prone terrain is suggestive of incorporation of elements of earthquake safety in these. In depth investigation of these buildings can bring to light hitherto unknown facts about this particular construction style and innovating upon traditional practices one can evolve a better suited construction dictum for the region. The present study thus aims to study earthquake safety related aspects of the traditional architecture of Uttarakhand.

[4] Rautela, Piyoosh, Kumar, S., Pande, M. and Pande, K.C., 2007, Impact of Earthquake Safety Initiatives in Uttarakhand (India), Disaster Mitigation and Management Centre, Dehradun, 50pp.

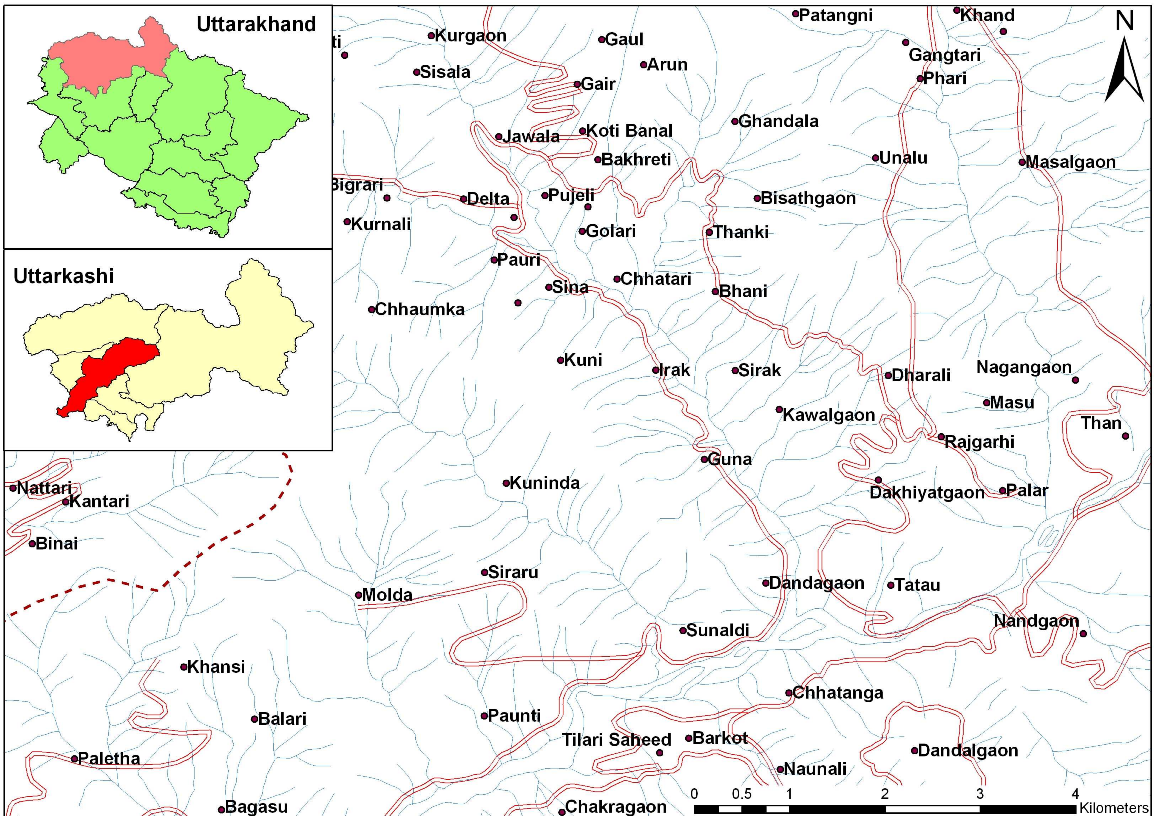

Fig. 4: Map showing the study area. Uttarkashi district and Naugaon block are highlighted in the maps of Uttarakhand and Uttarkashi respectively.

Rajgarhi area, to the north of Barkot across river Yamuna in Uttarkahi district of Uttarakhand (Fig. 4) has a large number of intact multistoried traditional structures (Fig. 5) in a number of villages in close proximity. This area was therefore selected for detailed investi

gations. A structured questionnaire was prepared to assess the perception of the masses towards structural safety related aspects as also their tradition. Detailed field investigation was resorted to for assessing the structural safety related aspects of this construction style.

Fig. 5: Traditional multistoried structures in Rajgarhi.

Perception of the Masses

Traditional practices of resource management reflect the community's resolve to safeguard its interests and these often draw strength for their continuation from religio - magical rites that are imbibed deep in popular belief. Continuation of these practices over generations indicates benefits drawn by the community by acting upon these. Insight into the popular belief and practices of the masses are therefore perceived to be the tools for assessing the strength of their traditional knowledge base.

The respondents: In order to assess the status of traditional practices relating to earthquake risk management people were interrogated with the help of a structured questionnaire that was also intended to be utilized for assessing the level of awareness of the masses on disaster related issues. Every effort was made to have representation of every section and group of the community and 50 persons were interrogated in detail in five villages in Rajgarhi area. As agriculture is the mainstay of the economy of the area, most of the interrogated persons engage in agrarian pursuits. The age of the respondents varied between 21 and 81 years with large proportion of the respondents (32%) falling in the age group of 40 – 50 years. Rampant illiteracy in the region is reflected in the low literacy levels of the respondents with 44 percent being illiterate or educated to primary level.

Earthquake safety features: Earthquake emerged as the major concern of the masses (90%) while landslide and flood accounted for the rest. Half the respondents rated the level of the perceived threat as being high while 34 percent rated this as being severe. Most respondents were proud of the rich architectural tradition of their region that is visually appealing and magnificent. Unlike inhabitants of the areas that have witnessed loss of traditional houses due to earthquake in the recent past[4] (as in Uttarkashi and Chamoli) most respondents consider traditional houses to be safer than the modern houses constructed with cement. **This suggests that the popular attitude can change in short time period when their beliefs prove to be wrong. The perceptions of the masses therefore reflects efficacy of their beliefs.** Most persons believe earthquake safety to be a cornerstone of the traditional construction practices but at the same time most (92%) could not pinpoint particular earthquake safety related feature of the traditional structures. Appropriate site selection and judicious use of wood together with the stone – wood bonding technique used in traditional buildings were perceived to provide the required levels of strength to these structures.

Site selection: As has also been revealed in the studies carried out in other parts of the State[4] the area under consideration exhibits an elaborate tradition of site selection and most people believe in its authenticity. Selection of stable and flat land is cited as the primary criteria for site selection. Local priest is reportedly consulted for ascertaining the suitability of the site selected for construction purposes. Majority (42%) holds that the advice is based on the observation of the soil of the proposed construction site. Inspection of the construction site (30%) and personal experience (20%) are considered to be other criterion for extending this advice. 6 percent of the respondents believe this advice to be based on astronomical calculations. **It seems that some persons based upon their experience and accumulated knowledge could assess and comment upon the bearing capacity of soil by examining soil texture, moisture content and the other related features.** This technique requires to be studied, documented and propagated (with necessary improvements where necessary). This would pave way for developing a quick and cost effective site selection methodology.

Foundation: The houses in the area are mostly observed to be constructed on raised and elaborate solid platform that adds to the stability of the structures by keeping the centre of gravity of the entire structure near the ground. This practice has perhaps resulted in the masses not paying much attention on the detailing of the foundation which is reflected in the response of the people. 60 percent of the respondents said that the depth of foundation varied between 2-3 feet. Unlike in other areas, construction is resorted to even if solid rock does not appear at the proposed construction site. People at the same time do not maintain long time gap between digging up of foundation and construction of the structure as is in vogue in most other areas of the State.

Seismic vulnerability and safety related aspects: Even though the area was jolted by Uttarkashi Earthquake of 1991 the masses do not seem to have any idea of differential vulnerability and majority (56%) said that all the houses would suffer equally in the event of an earthquake. All the respondents remembered previous earthquake in the region that caused some damage to the dwellings but only 56 percent could recall the year rightly. This might be owed to not so severe impact of the event in the area.

Most respondents (80%) consider good masonry work as the cornerstone of seismic safety. The rest were divided over site selection and detailing of the foundation. Most respondents agreed that strong and well constructed structures would minimize the losses likely to be incurred in the event of an earthquake. The respondents seemed to have heard of earthquake safe construction technology and they expressed willingness for spending a bit more for warding off the threat of their dwellings crumbling due to earthquake.

Masons: Traditional masons are preferred for construction works in the region. Familiarity with these masons apart from trust reposed by the masses on them, their knowledge and experience together with their cheap and easy availability are cited as the reasons for preferring them. It is hard to believe 67 percent of the respondents who assert that earthquake safe construction related knowledge of the masons is a consideration for entrusting construction work. All the respondents agreed that the masons with knowledge of earthquake resistant construction would be preferred and would therefore get more employment and wages.

Traditional structures: The area has tradition of erecting elaborate and magnificent multistoried houses that are locally identified as *Chaukhat*. Discussions however revealed that this term is used for four storied houses that are quite common in the region; five storied being identified as *Panchapura*. Masses in their local parlance (Garhwali) use different words to identify different floors of the house (ground floor, *kholi*; first floor, *manjua*; second floor, *baund*; third floor, *baraur*). This suggests common occurrence of multistoried houses in the region. Corrosion of the stone and wood used in the building is indicative of the antiquity of these structures. The respondents were however divided over the time of construction of these structures. A wide range (50 to 1700 years before present) was thus put forth as possible time of construction of these structures. Large proportion of the respondents (28%) however believed these to be constructed around 500 years before present. Two of the respondents in Guna village were confident enough to pinpoint the year of construction as being 1456.

Though majestic and visually appealing these multistoried houses were not spacious; these mostly have one single room on each floor towards the rear side of the structure with a small area in the front being utilized for placing wooden log with carved footholds for providing access to the

subsequent floor. The two areas are divided by a wall. The upper two floors have external balcony and the roofs of all the floors are not comfortably high. The kitchen is generally located in the top floor of the structure.
The purpose of constructing these not so occupant friendly multistoried houses with a single entry could not be established together with the technique and equipment employed for transporting and lifting heavy stone and wood panels. This huge structure could not certainly be built without supportive tools and implements.
Most respondents (92%) maintained that these structures were constructed to provide safety from thieves while protection from heavy snowfall was also cited as a reason. Whatever be the considerations behind constructing these elaborate structures, these were certainly not designed to cater to the comfort of the inhabitants. This seems the prime reason for a large number of these multistoried structures being put to disuse presently. These abandoned houses are deteriorating fast due to the lack of maintenance (Fig. 6) and require interventions for preserving the rich heritage of the region.
Prolonged non maintenance has taken its toll and many structures have turned too weak to be put to human use; but even the good ones are not being used. Poverty (18%), scarcity of wood (42%), lack of artisans and inconvenience in regular maintenance (18%), structural weakness due to prolonged non-maintenance (18%) and general inconvenience (2%) were cited as reasons for abandoning these multistoried houses.

Fig.6: Tradition in shambles: view of the abandoned multistoried structure at Koti Banal.

Field Observations

Ornate multistoried houses with abundant use of wooden beams are characteristic of Rajgari area. Similarity in the architectural principles and structural details suggest their possible evolution under one single architectural school. Locally available building material; long thick wooden logs, stones and slates are judiciously used for the construction of these structures. The height of these structures is observed to vary between 7 and 12 meters above the platform. These structures are observed to be four (*Caukhat*) and five (Panchapura) storied.

Raised platform: The multistoried traditional structures are observed to be constructed on raised and elaborate stone filled solid platform (Fig. 7) that is the continuation of the filled in foundation trench above the ground. In case of in situ rock being exposed the platform is observed to be raised directly over it. The height of the platform is observed to vary between 6 and 12 feet above the ground. Dry stone masonry is used for the construction of the platform.

Massive solid platform at the base of the structure helps in keeping the centre of gravity and centre of mass in close proximity and near to the ground. This minimizes the overturning effect of the particularly tall structure during seismic loading.

Fig. 7: Raised platform erected over in situ rocks to support the multi-storied structure.

Simplicity: The structures are observed to be constructed on a simple rectangular plan (Fig. 8) with the length and width varying between 4 and 8 meters. The ratio of the two sides of the structures is observed to vary between 1.1 and 1.4.

This is in keeping with the provisions of the building codes[5] that suggest that the building should have a simple rectangular plan and should be symmetrical both with respect to mass and rigidity so as to minimize torsion and stress concentration.

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[5] IS:4326, 1993, Indian standard code of practice for earthquake resistant design and construction of buildings, Second Revision, Bureau of Indian Standards, New Delhi.

Fig.8: Simple layout of the multi-storied structures.

The height of the structures above the platform is restricted to double the length of the shorter side (length or width). All the houses have a single small entry and relatively small openings. Strong wooden empanelment is provided around all the openings to compensate for the loss of strength. The internal architecture is split into staircase section and living section.

Walls: The walls of the traditional multistoried structure are raised by placing double wooden logs horizontally on the edge of the two parallel sides of the platform. The thickness of the walls is determined by the width of the logs (70 centimeters).

The other two walls are raised with well-dressed flat stones to the surface level of the logs placed on the other two sides. The walls are further raised to 30 cms by placing heavy, flat, dressed stones upon the wooden logs on the two sides and by placing another pair of wooden logs upon the stones on the other two opposite sides.

The four walls of the structure are thus raised using the wooden logs and dressed up flat stones alternately (Fig. 9). The structure is further reinforced with the help of wooden beams fixed alternately that run from the middle of the walls of one side to the other, intersecting at the center. This arrangement divides the structure into four parts and provides for joists supporting the floorboards in each floor of the building.

Fig.9: Wood – stone architecture of the walls of the traditional multi-storied structures.

On the fourth and the fifth floors a balcony is constructed with a wooden railing running around on all the four sides. Specially designed wooden ladders provided access to the different floors with the roof being laid with slates.

Interaction with the masses brought forth some interesting points regarding the architectural intricacy of the structure that included its being constructed on the principles somewhat similar to that of a framed structure. It is told that the wooden frame of the entire structure was finalized and this was then followed by filling up of the intervening voids by stone.

This has resulted in a mixed structure with two types of load sharing mechanisms; i) vertical load being taken care of by 1.5 feet thick walls running in all the four directions, and ii) horizontal load being taken care of by interconnected wooden joists running in both directions. On the two sides of the structure wooden beams are observed to be provided from outside (Fig. 10). It is held that these beams inserted from above were part of a special provision to enhance structure's seismic performance.

Salient points of the technology used in the construction of the multistoried traditional structures is also observed to be commonly used in other structures of the region as well. These include, i) the use of thick wooden logs running through the entire length of each of the walls alternately with heavy stones; ii) at the corners the edges of the pair of logs on the adjacent walls are joined together by hammering thick wooden nails through them. This has the effect of turning the structure into a single piece construction; and iii) all the windows, doorways, ventilators and floor- joists are joined to these well-secured pairs of logs and these further strengthened the structure.

Fig.10: The vertical wooden beam on the side walls is considered to be a seismic safety related provision.

Structural safety aspects

The architecture of the traditional buildings being investigated in the current study is woven around judicious use of wood. As a structural material, wood offers distinct advantage in earthquake performance over other materials; wood is strong yet lightweight, hence ground accelerations are unable to generate as much energy in wood buildings as in other buildings. As an added advantage, wood-frame systems flex more than other materials, thus absorbing and dissipating energy.

National Institute for Wood Products Research, Forintek, Canada has been involved in research related to the response of wooden buildings to earthquakes and based on the study of roughly half a million wood buildings involved in major earthquakes around the world over the previous 40 years Institute has developed reliable statistics pertaining to the wooden buildings. The study reveals that the North American style wood-frame structures, regardless of their age, perform better during earthquakes. Only 34 people were observed to have died due to failure of platform - frame buildings in seven studied earthquakes, while 40,000 persons were killed in 1999 Turkey Earthquake alone due to the collapse of mainly masonry and concrete structures. Not intending to discourage masonry and concrete structures in seismically vulnerable areas, above correlation is an attempt to drive home important message that these building systems require particularly careful adherence to design and construction standards for adequate seismic performance. Experience reveals wood based structures to be more tolerant.

Salient structural features of Koti Banal architecture: Inertial forces are a function of the weight of the object and therefore heavier buildings are subject to higher earthquake forces. Likewise, higher ground accelerations create more stress in the structure. The forces acting upon a structure during an earthquake are thus a function of the weight of the structures as also the magnitude of ground acceleration. Earthquake thus affects buildings differently depending on ground motion and building characteristics. The nature of seismic ground motion at a building site is dependent on a number of factors that include:

- Distance of building from the earthquake epicenter,
- Magnitude of the earthquake,
- Depth of the earthquake focus, and
- Soil conditions at the building site.

Nature of building response to an earthquake depends on the size of the building and its stiffness characteristics. Earthquakes that have high peak ground accelerations pose the greatest challenge to wood supported buildings. The inertial forces generated by the ground movement of the earthquake, concentrate lateral forces in the roof and floors where most mass of the building is concentrated. The forces in the roof and floors must be resisted by walls and entire structure must be adequately connected to the foundation. The following components of the wooden supported buildings are critical for seismic safety:

- Anchorage to the foundation,

- Strength and ductility of the walls,
- Strength and continuity of the horizontal elements (like roof, floor and ceilings), and
- Interconnection of the all farming elements.

The traditional buildings based upon Koti Banal architecture incorporate many features that improve its seismic performance. Structural capabilities of theses buildings include:

i) The mass and rigidity are distributed equally and symmetrically; the point of resultant earthquake forces (during an earthquake) thus tends to coincide with the point of resultant resisting forces. Torsion of the buildings is thus avoided or significantly reduced, which helps in shock resistance.

ii) The timber beams are housed in the walls in both the directions of the structure after 20 to 30 centimeter of squared rubble dry stone masonry brought to courses. The linked timber beams form a group of space stress system. The rigidity of the beams is nearly equal on cross ways so that its entire rigidity tends to be identity and its ability to resist deformation is coordinated.

iii) The beams used in the building are mostly rectangular in shape. The ratio of width to height of these beams is 2:3 which is a suitable section for a bending member. Sections of these wooden beams are larger than needed for adequate safety. The building system thus meets the required space rigidity as also strength requirements. This further helps in shock resistance.

iv) Wood is a elasto-plastic material with ability to absorb power of earthquake. Both housing and nailing techniques are resorted to for joining the wooden components incorporated in these structures (Fig. 11). This allows for minimal angular displacement. This kind of joint in the wooden beams incorporates advantages of both pin joint and the rigid joint and acts as a semi-rigid joint which is an additional advantage for shock resistance.

Fig.11: Housed and nailed joints used for fixing the wooden components of Koti Banal architecture.

v) Wood strength is high in the direction of the grain but weak across the grain. If designed and used properly, wood has very few structural limitations. Wood assemblies offer a high strength-to-weight ratio over those built with steel and concrete. This results in low inertial forces during an earthquake. The Koti- Banal architecture utilizes a number of wooden assemblies that help in resisting earthquake forces that are a function of the inertial force acting upon the structure.

vi) Wood-frame construction, structural walls and floors sheathed with structural wood panels employed in Koti Banal buildings are well recognized for providing superior performance against strong forces resulting from both wind storms and earthquakes. These walls and floors maintain high stiffness and strength in the design range, and if pushed to their ultimate capacity, tend to yield only gradually while continuing to carry high loads. These assemblies have high ductility which can absorb a great deal of energy before failure.

vii) Floors and roofs of wood construction are flexible diaphragms. FEMA 310[6] treats wood diaphragms as flexible but demands rigidity of the vertical elements. The vertical elevation of these buildings consists of rigid stone masonry wall that is adequate for providing the required strong support in the both directions of the building.

viii) The raised pedestal on the foundation together with the wooden beams at plinth level restrict earthquake vibration effects on the superstructure. It is accepted that stiffer soils promotes effective isolation[7]. The elevated, solid stone platforms help in consolidation of the soil at the foundation level and thus help in promoting isolation.

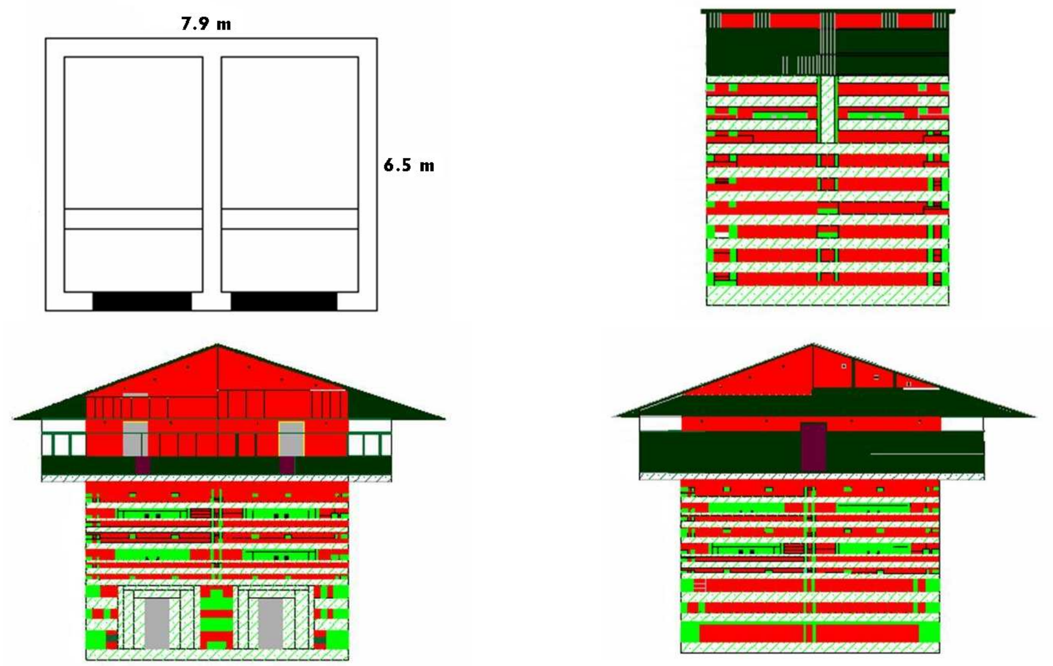

Fig.12: Plan, side, front and rear elevations of the Koti Banal structure.

Equivalent static lateral force analysis of the five storied Koti Banal structure: Most lateral forces acting on a structure during an earthquake emanate from inertia (mass) of the structures. These seismogenic forces are sudden, dynamic and can well be of immense intensity. The magnitude of lateral forces primarily depends upon the seismic zone, nature of soil or ground condition and fundamental building characteristics. The design base shear is first computed for the entire structure which is subsequently distributed along the height of the buildings based on simple formulas appropriate for buildings with regular distribution of mass and stiffness. The design lateral force obtained at each floor level is then distributed to individual lateral load

[6] FEMA 310, 1998, Handbook for seismic evaluation of buildings —A Prestandard, American Society of Civil Engineers.

[7] Mayes, R.L. and Naiem, F., 2001, The seismic design handbook, Naiem, F., Editor, Kluwer Academic Publishers, 735 pp.

resisting element depending upon floor diaphragm action. Methodology put forth by IS 1893 (Part 1):2002[8] has been utilized for this work.

Design seismic base shear calculation: Given below are detailed calculations for the Koti Banal structure (Fig. 12).

Building data

Live load data

Live load on roof	=	1.0 KN/m^2 (For seismic calculation =0)
Live load on floor	=	1.0 KN/m^2

Dead Load data

As per IS: 875 (Part 1) - 1987[9]

Floor

Thickness of wooden floors	=	22 mm
Weight of floors	=	0.16 KN/m^2
Thickness of wall	=	450 mm
Weight of wall	=	11.5 KN /m^2

(Assuming weight density of stone masonry = 27 KN/m^2)

Roof

Inclined or tilted roof having slates on battens

Weight of roof	=	0.50 KN/m^2

(Weight acting vertically on horizontal projection being multiplied by cosine of roof angle to obtain weights normal to the roof surface)

Seismic data

Seismic Zone	=	V
Zone factor (Z)	=	0.36
Importance factor	=	1.5 (Historical categories)
Response Reduction factor (R)	=	3.0 (as per IS : 1893 (Part 1) :2002[7])

For Rocky or hard soil types average response acceleration coefficients are as given below.

$$\frac{S_a}{g} = \begin{cases} 1 + 15T, 0.00 \le T \le 0.10 \\ 2.50, 0.10 \le T \le 0.55 \\ 1.36/T, 0.55 \le T \le 4.00 \end{cases}$$

Direction of seismic force	=	E-W and N-S directions	

Seismic weight calculations

Dead load and Live Load at roof level

Weight of roof	=	0.50×6.8×6.5×0.95×2.0	
	=	41.5 KN	------------------ (i)
Weight of E-W walls	=	[{1/2×1.6×4.0)+0.7×4.0}×2.0×2.0×27]/2	
	=	145.8 KN	------------------ (ii)

Assuming half the weight of walls at top storey to be lumped at roof.

Weight of N-S walls	=	6.5×0.7×0.45×2×27/2	
	=	55.28 KN	------------------ (iii)
Weight of live load (LL)	=	0	

(For seismic calculation, LL on roof is zero)

Weight at roof level	=	i + ii + iii
	=	41.50 + 145.8 + 55.28

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[8] Indian Standard: 1893, Part 1, 2002, Criteria for earthquake resistant design of structures, Bureau of Indian Standards.

[9] IS: 875(Part 1), 1987, Code of practice for design loads for buildings and structures, Bureau of Indian Standards.

	=	242.6 KN

Dead Load and Live load at floor levels

Ground Floor

Weight of floor	=	7.9×6.5×0.16
	=	8.3 KN
Weight of Walls		
E- W walls	=	7.9×2.3×0.45×27×2.0
	=	441.53 KN
N-S walls	=	6.5×2.3×0.45×27×2.0
	=	363.30 KN
Weight of live load (LL)	=	1.0×7.9×6.5
	=	51.4 KN

First Floor

Weight of floor	=	7.9×6.5×0.16
	=	8.3 KN
Weight of Walls		
E- W walls	=	7.9×1.8×0.45×27×2.0
	=	345.5 KN
N-S walls	=	6.5×1.8×0.45×27×2.0
	=	284.3 KN
Weight of live load (LL)	=	1.0×7.9×6.5
	=	51.4 KN

Second Floor

Weight of floor	=	7.9×6.5×0.16
	=	8.3 KN
Weight of Walls		
E- W walls	=	7.9×1.8×0.45×27×2.0
	=	345.5 KN
N-S walls	=	6.5×1.8×0.45×27×2.0
	=	284.3 KN
Weight of live load (LL)	=	1.0×7.9×6.5
	=	51.4 KN

Third Floor

Weight of floor	=	7.9×6.5×0.16
	=	8.3 KN
Weight of Walls		
E- W walls	=	7.9×2.2×0.45×27×2.0
	=	422.33 KN
N-S walls	=	6.5×2.2×0.45×27×2.0
	=	347.5 KN
Weight of live load (LL)	=	1.0×7.9×6.5
	=	51.4 KN

The half weight of walls of the upper story and half weight of walls of the lower storey are lumped in the upper stories. The lumped mass of each floors are as given below.

W_{Roof}	=	242.6 KN
W_{Ground}	=	777 KN
W_{First}	=	689.45 KN
W_{Second}	=	759.5 KN
W_{Third}	=	640.8 KN
Total seismic weight of building	=	242.6+777+689.45+759.5+640.8

= 3109.35 KN

Time period calculations: The approximate fundamental natural period of a wooden supported masonry building are calculated as per Clause 7.6.2 of IS: 1893 (Part 1): 2002[7] that defines

$$T_a = 0.09h/\sqrt{d}$$

Where,

h = height of building in meters,

= $2.3_{Ground} + 1.8_{First} + 1.8_{Second} + 2.2_{Third} + 2.3_{Top}$

= 10.4 m for E-W walls

and

h = $2.3_{Ground} + 1.8_{First} + 1.8_{Second} + 2.2_{Third} + 0.7_{Top}$

= 8.8 m for N-S walls,

d = Base dimension of building at the plinth level (in meters) along the considered direction of lateral force (i.e. 7.9 m, assuming earthquake in E-W direction and 6.5 m assuming earthquake in N-S direction)

T_a = 0.33 seconds assuming earthquake in E-W direction

and

T_a = 0.23 seconds assuming earthquake in N-S direction

S_a/g = 2.5 for both directions of earthquakes

$$A_h = \frac{ZIS_a}{2Rg} = \left(\frac{0.36}{2}\right)\left(\frac{1.5}{3}\right)(2.5) = 0.225$$

The total design lateral base shear (V_B) along the direction of motion is given by,

V_B = A_hW

= 0.225×3109.35 KN

= 699.6 Say 700 KN

The design lateral base shear (V_B) is distributed along the height of building and the lateral forces at each floor level are calculated by using the following equation:

$$Shearforce = V_B \frac{W_i h_i^2}{\sum_{i=1}^{n} W_i h_i^2}$$

Distribution of lateral forces: Figure 13 shows the distribution of lateral forces in box type shear wall buildings. In order to successfully transfer the seismic forces to the ground building should necessarily have a continuous load path. The general load path for the Koti Banal structure is as follows; earthquake forces originating in all the elements of the building are delivered through the transverse walls of the building and it is bent between the floors. The lateral loads are transmitted from these transverse walls to the side shear walls by horizontal floor and roof diaphragm. The diaphragms distribute these forces to vertical resisting components such as shear walls and vertical resisting elements if any, which transfer the forces into the foundation. The diaphragm must have adequate stiffness and strength to transmit these forces. It is observed that in Koti Banal buildings the floors are made of 20-22 millimeter thick wooden planks that are expected to exhibit high degree of flexibility and all the walls are 45 centimeter dry dressed stone that are highly rigid. The above thus satisfactorily fulfill the flexible diaphragm conditions.

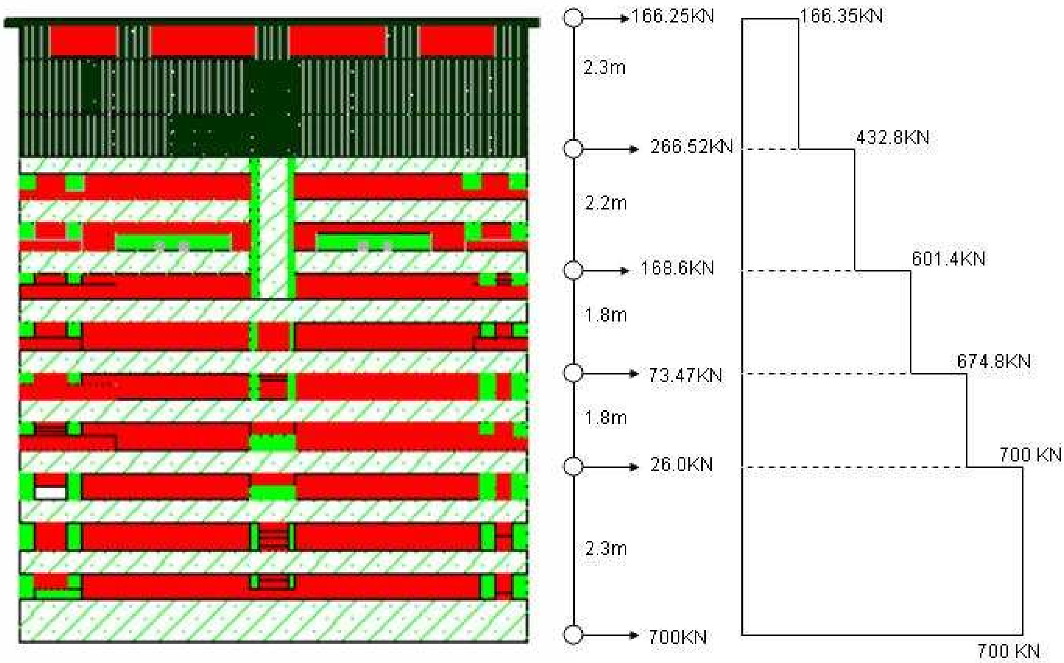

Fig.13: Figure showing distribution of lateral forces in Koti Banal structure.

Seismic performance of Koti Banal structure: Using the equivalent static method the design base shear for the Koti Banal structure has been computed to be of the order of 700 KN that works out to be 23 percent of total seismic weight of the building. Detailed investigation of a number of buildings in the area clearly reveal that the age old structural systems are still intact and even the nonstructural components have not been damaged by the seismic activities despite these being located in the most severe zone of earthquake damage risk (Zone V) and having experienced many earthquakes in the past. The age of the buildings clearly suggests that these would have experienced at least DBE[10] ground shaking in their life span.

Table 1. Categories of wooden buildings and design method.

Seismic design type of building and construction		**Seismic elements**	**Seismic design method**
Traditional wooden buildings	Shrine, temple, pagoda	Frame, wall and rocking effect	Not applied or special analysis
Detached wooden houses	Conventional	Shear wall (bracing or board)	Effective wall length method
	Base isolation		Special analysis
Heavy timber structure	Ordinary frame	Moment resisting frame and truss	Working stress (Allowable stress) design method
High-rise wooden building		Moment resisting frame and shear walls	Performance based design method

The building system is analyzed using equivalent static method but it is required that detailed analysis be undertaken using advanced techniques like response spectrum, linear time history, and pushover that provide definitive insight to the building system. It is also required to evaluate the response of the building system under tri-directional loads as it is established that simultaneous

[10] IS 1983 (Part 1): 2002 defines DBE as the earthquake which can reasonably be expected to occur at least once during the design life of the structure.

tri-directional seismic motions does influence the response of the building system[11].There are many types of wooden building in the various parts of world. These have different seismic elements and accordingly different seismic design method[12] (Table 1) has to be employed for assessing their seismic performance.

The Koti Banal structures fall in high-rise wooden building category having moment resisting cross beams and stone masonry shear walls. Performance based design method is thus most suited method for studying the seismic performance of these buildings. In situ testing is also required to be carried out for assessing the strength of stone walls as also wood employed for construction. Finite element method (FEM) is the most suited modeling method for such complex masonry-wooden combination buildings.

[11] Sweemey, S.C., Horney, M.A. and Orton, S.L., 2004, Tri-directional seismic analysis of an unreinforced masonry building with flexible diaphragms, US Army Corps of Engineers, Engineering Research and Development Centre (ERDC/CERL TR – 04 – 06).

[12] Koshihara, M. and Sakamoto, I., 2005, Seismic performance of wooden buildings in Japan, Japan – Taiwan International Workshop on Urban Regeneration 2005, Maintenance and Green Material, 23-27 November, 2005, Taipei, Taiwan, 73 – 74.

Architectural Differences

During the course of the field work in the area most buildings were observed to follow more or less similar architectural principles that include:

1. Simple rectangular plan,
2. Use of horizontal wooden beams,
3. Low roof height,
4. Shear walls,
5. Small openings,
6. Projected balcony on the upper stories,
7. Solid raised platform at the base.

Fig.14: New construction in front of the magnificent structure at Koti Banal would subdue the impact of the tradition.

It is perceived that these buildings were constructed under the influence of one single architectural school that accorded least importance to the comfort of the inhabitants. The structure at Koti Banal is observed to be the most magnificent of these buildings and therefore the architectural style is being termed as Koti Banal type. Unplanned construction taking place right in front of this structure might amount to defacing the traditional structure (Fig. 14).

Fig.15: View of the multistoried traditional structure at Gona.

Fig.16: Internal wall with a door on the first floor. This wall lacks continuity from the ground floor.

Equally impressive structure is observed in Gona village (Fig. 15). Detailed examination of the structure reveals that the principles of Koti Banal architecture are not strictly adhered to in this structure. The roofs of this structure are observed to be comfortably high while internal layout of the walls varied in every floor (Fig. 16). Detailed observations reveal that the basic elements of seismic safety have been compromised with in this structure.

The Gona structure could well represent earlier stages of the evolution of the Koti Banal architecture whereby experiments on these lines might have led to the evolution of the perfect form. There however exists possibility of this structure representing later modifications to the original style in an attempt to make these structures more occupant friendly.

It is observed that the middle portion of the Gona structure has bulged out which might be due to violation of Koti Banal guidelines. Collapse of the structure might jeopardize human lives.

Age of the Structures

Radiocarbon (C^{14}) dating is probably one of the most widely used and best known absolute dating methods for organic materials. It was developed by J. R. Arnold and W. F. Libby in 1949. Its development revolutionized archaeology by providing a means of dating deposits independent of artifacts and local stratigraphic sequences.

Radiocarbon dating relies on a simple natural phenomenon. As the earth's upper atmosphere is bombarded by cosmic radiation, atmospheric nitrogen is broken down into an unstable isotope of carbon (C^{14}). This unstable isotope is brought to earth by atmospheric activities, such as storms and gets fixed in the biosphere. C^{14} reacts identical to C^{12} and C^{13} and thus gets attached to complex organic molecules through photosynthesis in plants and becomes part of their molecular makeup. Animals eating these plants absorb C^{14} as also the stable isotopes. This process of ingesting C^{14} continues all through the life of the plant or animal.

The C^{14} within an organism decays continually into stable carbon isotopes, but since the organism is continually absorbing C^{14} during its life the ratio of C^{14} to C^{12} remains about the same as the ratio in the atmosphere. When the organism dies, the ratio of C^{14} within its carcass begins to gradually decrease. Half life of C^{14} is 5,730 years; the time in which C^{14} decays to half the original quantity.

Using radiocarbon dating technique, almost any sample of organic material can be directly dated. As with other techniques there are however some limitations:

- First, the size of the organic sample is important; larger samples being better as some matter is removed in purification and distillation. New techniques for working with very small samples have however also been developed.
- Second, great care must be taken in collecting and packing samples to avoid contamination by more recent carbon.
- Third, because the decay rate is logarithmic, radiocarbon dating has significant upper and lower limits. It is not very accurate for fairly recent deposits as decay is not significant and thus the error factor (the standard deviation) is often larger than the date obtained. The practical upper limit is about 50,000 years, because so little C^{14} remains after almost 9 half lives that it may be hard to detect and obtain an accurate reading, regardless of the size of the sample.
- Fourth, the ratio of C^{14} to C^{12} in the atmosphere is not constant. This variation is owed to changes in the intensity of the cosmic radiation bombardment of the earth, and changes in the effectiveness of the Van Allen belts and the upper atmosphere to deflect that bombardment. For example, because of the recent depletion of the ozone layer in the stratosphere, we can expect there to be more C^{14} in the atmosphere today than there was 20-30 years ago. To compensate for this variation, dates obtained from radiocarbon

laboratories are corrected using standard calibration tables. It is therefore important to calibrate the C^{14} dates.

Time of construction of the traditional buildings is important for assessing the archeological relevance of these structures as also for correlating the architectural style with other contemporary styles. Having been unable to assess the time of construction through interaction with the masses it was decided to resort to radiocarbon dating technique for the same. Wood samples were thus collected from the wooden panels used in the buildings and the same were analysed and calibrated at Birbal Sahni Institute of Palaeobotny, Lucknow. In order to address the issue of architectural differences in the structure observed at Gona and Koti Banal wood samples from both the structures were dated using radiocarbon (C^{14}) techniques. **The Koti Banal structure (Fig. 10 and Fig. 14) was dated to be 880 ± 90 years before present while the Gona structure (Fig. 15) was dated to be 728 ± 60 years before present.**

The radiocarbon dates bring forth an important fact that the principles of earthquake safety had evolved in the region quite early. The detailing of the structures suggests that the ones designing the structures had fairly good idea of the forces acting upon the structure during an earthquake event; well before the evolution of the concept of force by Sir Isaac Newton (1643 –1727).

Seismic performance of these structures has been tested by Kumaun Earthquake of 1720 and Garhwal Earthquake of 1803 that are considered to be highly damaging and this earthquake safety conscious school of architecture might well have started after the earthquake of 1100 AD that is believed to have devastated large tracts across India.

Evolution of any tradition is a long process that includes testing of certain features and evolving the same on lines observed to be working. At the same time certain time tested features are replaced to suite convenience and emerging needs without seriously dwelling upon their impact.

It was interesting to note that the multistoried structure at Gona though built using similar architectural style is more occupant friendly with the roofs being sufficiently high. Radiocarbon dates reveal this structure to be younger than the one observed in Koti Banal. This structure digresses from seismic safety norms and does not provide for shear walls. This is thus a later digression rather than an earlier experimentation leading to architectural refinement.

Conclusion

Detailed investigations in Rajgarhi area of Uttarkashi suggest existence of a traditional system for ensuring seismic safety of the structures, as also evolution of a distinct and magnificent architectural style.
The people inhabiting the area had developed an elaborate system for selecting appropriate site for construction. Some persons based upon their experience and knowledge are believed to assess and comment upon the bearing capacity of soil by examining soil texture, moisture content and the other related features. Elements of this age old traditional practice need to be studied, documented, innovated and propagated (with necessary improvements where necessary) so as to evolve a readily available, easy and cost effective tool for assessing site suitability.
There existed tradition of erecting structures over an elaborate, solid and raised stone platform that reduced overturning effect in these particularly high structures.
The construction style was observed to be quite distinct and a large number of structures in the region were observed to be built on similar fashion that is indicative of evolution of this particular school of architecture in the region. This is being termed Koti Banal architecture after the most magnificent representative of this school.
The Koti Banal architecture attained its zenith around 880 ± 90 years before present as is evident from the dating of the Koti Banal masterpiece. The main constituents of Koti Banal architectural style are:

- **vii) Simple layout of the structure,**
- **viii) Construction on elaborate, solid and raised platform,**
- **ix) Judicious use of locally available building material,**
- **x) Incorporation of wooden beams all through the height of the building at regular intervals,**
- **xi) Small openings and**
- **xii) Shear walls.**

Koti Banal architecture however did not cater for the comfort of the inhabitants and was totally utilitarian. This was perhaps the reason for the introduction of aberrations in the original style as early as 728 ± 60 years before present as is evident from the dating of Gona structure (Fig. 15).
The Koti Banal architecture needs to be studied and documented in much more detail. Intricacies of this age old construction style have the potential of unfolding a new line of construction that might be better suited even in present ground realities of the region.
It is observed that many old structures of Koti Banal style are being put to disuse and are deteriorating fast due to the lack of maintenance (Fig. 6). People are even demolishing these old structures voluntarily so as to use the disassembled building material for the

construction of new and modern dwellings. Masses therefore need to be made aware and educated on the issue of protecting these heritage structures.

Representatives of Koti Banal architecture together with the Koti Banal structure (Fig. 10 and Fig. 14; built around 880 ± 90 years before present) need to be protected as heritage buildings by the Government (Department of Culture) so as to enable the coming generations to have a glimpse of the magnificent architectural tradition of the region. This would also provide researchers with an opportunity of studying this majestic architectural style of Uttarakhand in detail.

There also exists possibility of promoting ecotourism in the region by weaving a suitable marketing strategy around these age old traditional structures. This would generate much sought after gainful employment opportunities in the region.

Unplanned construction around the representative structure at Koti Banal would soon subdue its magnificence (Fig. 14). Construction around these heritage structures needs to be regulated by law.

It is observed that the traditional masons that had mastered the art of stone – wood construction are fast switching over to cement based construction due to the lack of patronage. Since they are not propagating intricacies of the traditional construction practices, basic elements of the traditional construction style would soon be lost. It is therefore necessary to study and document the finer elements of traditional construction practice. Innovating on the traditional building material and practices would give a lease of life to this construction style.

The region had a tradition of erecting structures over raised platform and therefore detailing of the foundation is not accorded its due share of importance. The masons practicing in the region therefore need to be educated on this important aspect.

Disaster Risk Management Programme

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Ministry of Home Affairs
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उत्तराखण्ड शासन

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