Earthquake-safe Koti Banal architecture of Uttarakhand, India

Piyoosh Rautela* and Girish Chandra Joshi

Disaster Mitigation and Management Centre, Department of Disaster Management, Government of Uttarakhand, Uttarakhand Secretariat, Rajpur Road, Dehradun 248 001, India

Despite being located in the seismically highly vulnerable region, Uttarakhand shows an elaborate tradition of constructing multistoried houses. Both the local dialects of the region (Kumaoni and Garhwali) have unique words for identifying four different floors of a building. This suggests common occurrence of multistoried structures in the region. Rajgarhi area, Uttarkashi District has a large number of intact multistoried traditional houses with marked antiquity and distinct construction style. Detailed investigations suggest that the region had evolved a distinct and elaborate earthquake-safe construction style as early as 1000 yrs BP. This is known as the Koti Banal architecture. It exhibits elaborate procedures for site selection, preparing the platform for raising the structure, as also for detailing the entire structure constructed on principles somewhat akin to that of framed structures of the present times. Locally and then abundantly available wood was judiciously used in these structures. The structural detailing suggests that those responsible for designing these buildings had a fairly good idea about the forces likely to act upon the structure during an earthquake. The significant features of the Koti Banal architecture include: (i) simple layout, (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. The Koti Banal architecture, however, did not cater to the comfort of the inhabitants. This was perhaps responsible for the introduction of aberrations in the original construction style as early as 728 ± 60 yrs BP.

Keywords: Earthquake-resistant construction, Koti Banal architecture, multistoried structures.

THE north-northeastward drift of the Indian plate, responsible for the evolution of the Himalayan orogen, has not yet seized. The ongoing build-up of strain due to this movement is responsible for frequent earthquakes in the region. The entire Himalayan terrain is recognized as being highly vulnerable to earthquakes[1,2]. In the past the region has been jolted by four great earthquakes (magnitude >8 on the Richter scale)[3]: 1897 Shillong earthquake, 1905 Kangra earthquake, 1934 Bihar–Nepal earthquake and 1950 Assam earthquake, apart from Kumaun earthquake of 1720 and Garhwal earthquake of 1803. Regions between the rupture zones of the great earthquakes are recognized as seismic gaps that are interpreted to have accumulated potential slip for generating future great earthquakes. Uttarakhand is located in the seismic gap of the 1934 Bihar–Nepal earthquake and 1905 Kangra earthquake, and is categorized under zones IV and V of the Earthquake Risk Map of India[4]. 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) in the recent past.

Human response to emerging exigencies has resulted in the fine-tuning of resource management practices, as also life-support strategies, 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. Communities residing in areas often affected by earthquakes were quick to understand the fundamental premise of earthquake safety, that the key to avoiding loss of human lives lies in ensuring safe construction. This fundamental understanding led to the evolution of innovative practices for minimizing human losses emanating from structural collapse.

Despite experiencing earthquakes (‘chalak’ in Kumaoni) quite frequently, multistoried houses are common in Uttarakhand and apart from the cattle sheds (‘channi’ in Kumaoni), one can hardly locate a single-storied, traditional house in the region. Unique words are used for identifying as many as four different floors in the two local dialects of the region, i.e. 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 used, a unique word is not generally incorporated in any language. This in turn proves the common occurrence of multistoried houses in the region. The zeal to protect the community, by utilizing accumulated knowledge and experimenting with locally available building material, paved the way for the evolution of a unique architectural style that exhibits

*For correspondence. (e-mail: piyooshrautela@gmail.com)

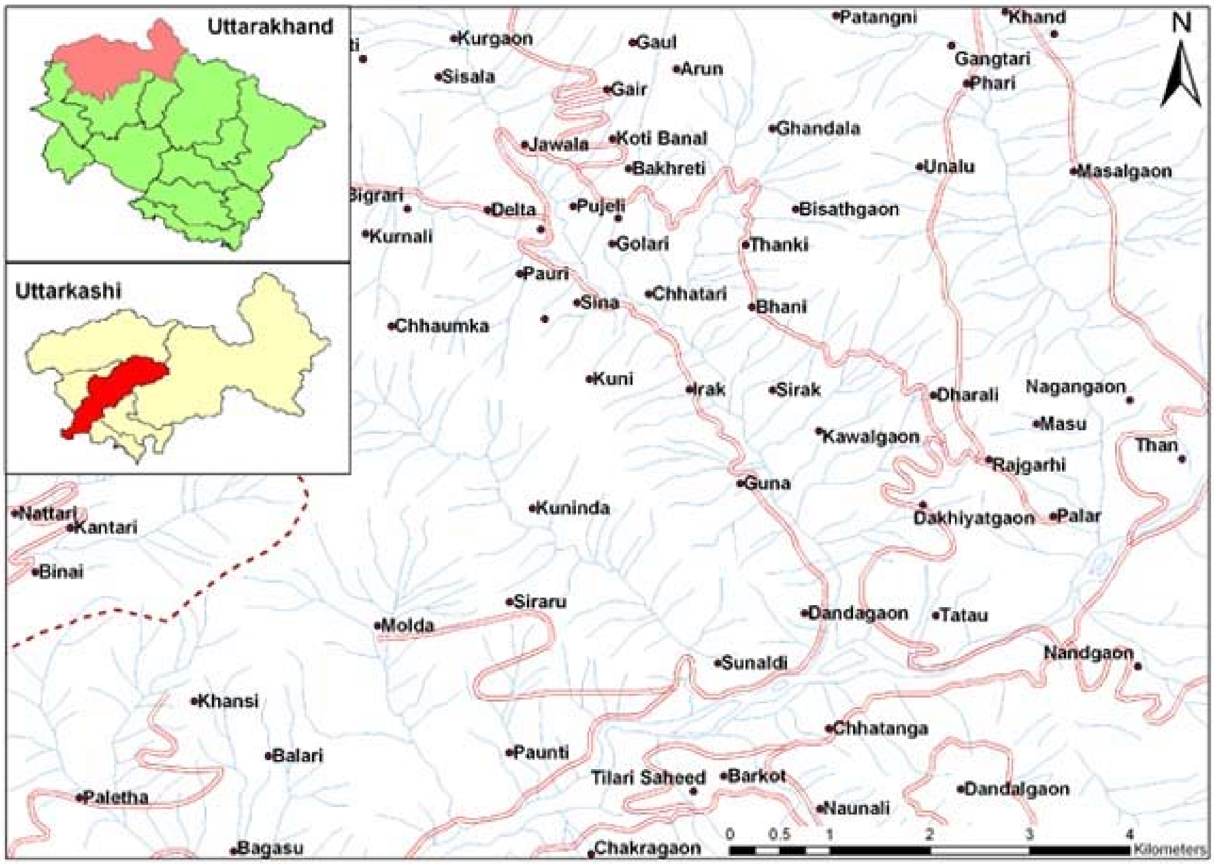

Figure 1. Location map of the study area.

structural evolution trends whereby dry stone masonry, as also stone–lime/mud/clay mortar masonry was judiciously used with wood to provide appropriate strength and flexibility to the structures.

In the Yamuna and Bhagirathi valleys of the Garhwal region four to five-storied traditional structures can still be seen (identified as chaukhat, four-storied or panchapura, five-storied). These age-old structures must have witnessed many earthquakes and in the absence of the elements of earthquake safety, these would have long been razed to ground.

Detailed investigations were carried out in the area to the north of Barkot across Yamuna (Figure 1), for establishing elements of earthquake safety in these traditional houses. Many villages (Dakhiyatgaon, Guna, Koti Banal, Dharali) in this area have a large number of intact multistoried traditional structures (Figure 2). A structured questionnaire was utilized for assessing the perception of the masses towards structural safety-related aspects, as also their tradition.

Field observations

Ornate, multistoried houses with abundant use of wooden beams are characteristic of the Rajgari area. Similarity in the architectural principles and structural details suggest their possible evolution under a single architectural school referred to as Koti Banal architecture, after the five-storied structure observed in Koti Banal village (Figure 3). The wooden frame of the entire structure was finalized first and then the intervening voids were filled with stones, which is similar to modern-day framed construction. This has resulted in a mixed structure with two types of load-sharing mechanisms: (i) vertical load taken care of by 1.5 ft thick walls running in all the four directions, and (ii) horizontal load taken care of by interconnected wooden joists running in both directions. On the two sides of the structure, wooden beams are provided from the outside. These beams inserted from above were part of a special provision to enhance the seismic performance.

The multistoried traditional structures are constructed on raised and elaborate stone-filled solid platform which is the continuation of the filled-in foundation trench above the ground. The height of the platform varies between 2 and 4 m above the ground and dry stone masonry is used for its construction. A 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 the ground. This minimizes the overturning effect of the particularly tall structure during seismic loading.

The structures are observed to be constructed on a simple rectangular plan (Figure 4) with the length and width varying between 4 and 8 m. 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.

Figure 2. Simple but majestic architecture of traditional houses in Dharali village.

Figure 3. Five-storied structure of Koti Banal architecture constructed 880 ± 90 yrs BP.

The height of these structures varies between 7 and 12 m above the platform and 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 which is in accordance with the provisions of the building codes[5]. 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.

The walls 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 cm). The other two walls are raised with well-dressed flat stones to the level of the logs placed on the other two sides. The walls are further raised to 30 cm 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. The structure is further reinforced with the help of wooden beams fixed alternately, that run from the middle of the walls on one side to the other, intersecting at the centre. This arrangement divides the structure into four parts (Figure 4) and provides for joists supporting the floorboards in each floor of the building. 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.

Structural safety related aspects

The Koti Banal architecture is woven around judicious use of wood, which as a structural material offers distinct

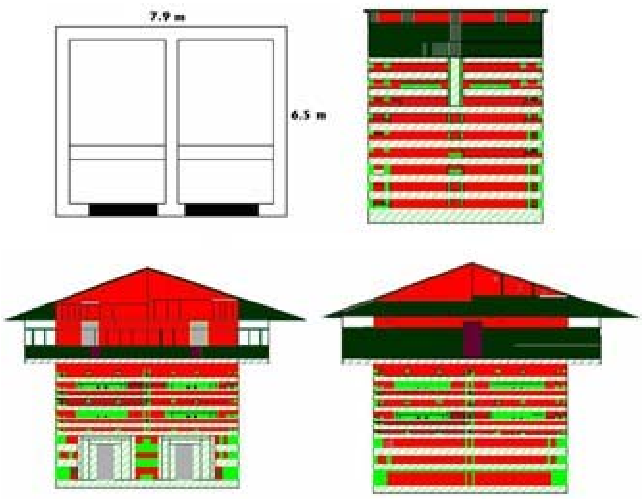

Figure 4. Plan and elevation of the five-storied structure given in Figure 3.

advantage in earthquake performance over other materials. Wood being both strong and lightweight, ground accelerations are unable to generate as much energy in wood buildings as in the ones constructed with other materials. As an added advantage, wood-frame systems flex more than other materials, thus absorbing and dissipating energy.

The forces acting upon a structure during an earthquake are a function of the weight of the structure as also the magnitude of ground acceleration, while the nature of building response to an earthquake depends on the size of the building and its stiffness characteristics. 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. This force must be resisted by the walls and the entire structure must be adequately connected to the foundation. The Koti Banal architecture incorporates a number of distinct features that improve its seismic performance. These include:

(i) The mass and rigidity are distributed equally and symmetrically; the point of the resultant earthquake forces (during an earthquake) thus coincides with the point of the 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 directions of the structure after 20–30 cm 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 identical 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 those 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 the forces of earthquake. Both housing and nailing techniques are resorted to for joining the wooden components incorporated in these structures (Figure 5), which allows for minimal angular displacement. This kind of joint incorporates advantages of both pin joint and rigid joint and acts as a semi-rigid joint, which is an additional advantage for shock resistance.

(v) If designed and used properly, wood has 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 universally recognized as 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) Wooden floors and roofs of Koti Banal buildings are flexible diaphragms. FEMA 310 treats such diaphragms as flexible, but demands rigidity of the vertical elements[6]. The vertical elevation of these buildings consists of a rigid stone masonry wall that is adequate for providing the required strong support in 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 stiff soil promotes effective isolation[7]. The elevated, solid stone platform helps in consolidation of the soil at the foundation level and thus helps in promoting isolation. The flexibility of the structure determines its performance during a given earthquake motion. The form of the earthquake motion at the base of the structure can however be modified by the properties of the soil through which the earthquake waves travel. If the soil underlying the structure is soft, the high frequency content of the motion may get filtered out, and the soil may produce long-period motion. Thus it is safe to use stiff platform for effective isolation[8].

Figure 5. Housed and nailed joints used for fixing the wooden components of the Koti Banal architecture.

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 be of immense intensity. The magnitude of lateral forces primarily depends upon the seismic zone, nature of the soil or ground condition and fundamental building characteristics. The design base shear is first determined for the entire structure. It is subsequently distributed along the height of the building on the basis of appropriate equations 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 resisting elements depending upon floor diaphragm action. Methodology put forth by IS1893 (Part 1):2002 has been utilized for this work[9]. The design seismic base shear (V_B) is calculated to be the multiplicative product of horizontal seismic coefficient (A_h) and seismic weight (W). The horizontal seismic coefficient (A_h) is calculated using the formula

$$A_h = \frac{(Z/2)(S_a/g)}{(R/I)},$$

where Z is the zone factor (0.36 for zone V). Average response acceleration coefficient (S_a/g) is obtained from the relationship between (S_a/g) and time period (T) of vibration for different soil types. The present structure has been constructed on rocky and hard soil for which, according to Clause 6.4.5 IS:1893 (ref. 9)

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

The fundamental natural period (T) for the structures can either be established by experimental observations on a similar type of building or can be calculated using any rational analysis method. In the absence of these, the fundamental natural period of vibration (T) is calculated according to Clause 7.6.2 of IS:1893 (ref. 9). The time period (T) for the studied building has thus been calculated using $T_a = 0.09h/\sqrt{d}$, where h is the height of building (in m) and d is the base dimension of the building at plinth level (in m) along the considered direction of the lateral force. Importance factor (I) of 1.5 is used for the calculations, as the structure under question is of historical importance. A response reduction factor (R) of 3.0 is considered for the structure, as the horizontal wooden beams are observed to act as seismic bands at different levels in the load-bearing stone masonry building.

The design seismic base shear force for the Koti Banal structure (Figure 3) along the direction of motion is calculated to be of the order of 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 using the equation

$$\text{Shear force} = V_B \frac{W_i h_i^2}{\sum_{i=1}^{n} W_i h_i^2},$$

where W_i is the seismic weight of the ith floor, h_i is the height of floor i measured from base and n, the number of storeys in the building, is the number of levels at which the masses are located.

Figure 6 shows the distribution of lateral forces in the Koti Banal structure. In order to successfully transfer the seismic forces to the ground, a 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 they are 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. Floors of the Koti Banal structure are made of 20–22 mm thick wooden planks that are expected to exhibit high degree of flexibility, while all the walls are 45 cm dry dressed stone that are highly rigid. These satisfactorily fulfil the flexible diaphragm conditions.

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% of total seismic weight of the building. Detailed investigation of a number of buildings in the area clearly reveals that

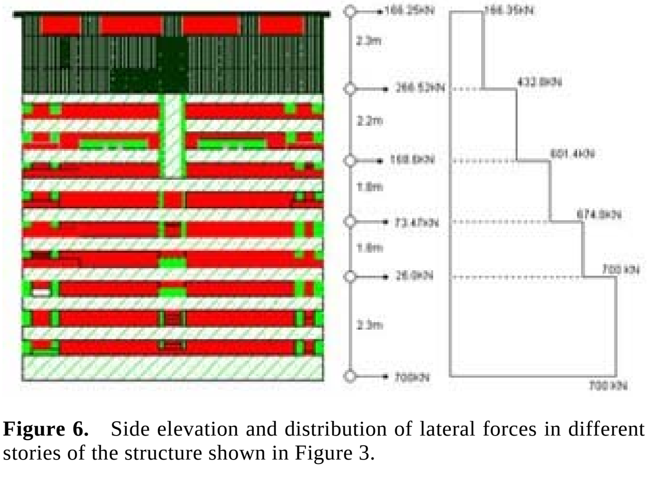

Figure 6. Side elevation and distribution of lateral forces in different stories of the structure shown in Figure 3.

the age-old structural systems are still intact and the non-structural 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 (Figure 7). The age of the buildings clearly suggests that these would have experienced at least design basis earthquake (DBE)[9] ground-shaking in their lifespan.

The building system analysed using equivalent static method requires detailed analysis using advanced techniques (like response spectrum, linear time history and pushover). The influence of tri-directional seismic motions on the response of the building system also needs to be evaluated[10]. The seismic design method to be employed for assessing seismic performance of wooden buildings is based upon its seismic elements (Table 1)[11]. The Koti Banal structures fall under the high-rise wooden building category, having moment-resisting cross beams and stone masonry shear walls. Performance-based design method is thus most suited for studying their seismic performance. *In situ* testing is also required for assessing the strength of the stone walls as also wood employed for construction. Finite element method would be the most suited modelling method for such complex masonry–wooden combination buildings.

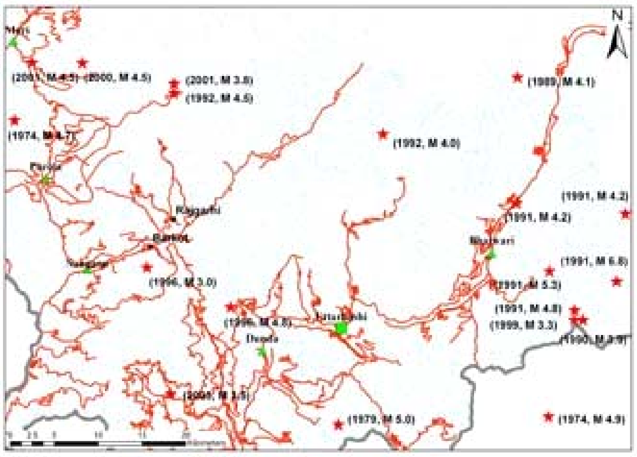

Figure 7. Map of the study area showing epicentres of past earthquakes (source: USGS).

Table 1. Categories of wooden buildings and their design methodologies

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

Antiquity of the structures

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. Radiocarbon dating of the wood samples collected from the panels used in the buildings was analysed and calibrated at the Birbal Sahni Institute of Palaeobotany, Lucknow. The Koti Banal structure (Figure 3) was dated to be 880 ± 90 yrs BP, while the one at Guna was dated to be 728 ± 60 yrs BP.

The radiocarbon dates show that the principles of earthquake safety had evolved in the region quite early. The detailing suggests that those designing the structures had a fairly good idea of the forces acting upon the structure during an earthquake event.

Seismic performance of these structures has been tested by the Kumaun earthquake of 1720 and Garhwal earthquake of 1803, that are considered to be highly damaging. This earthquake safety-conscious school of architecture might well have started after the earthquake of AD 1100 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 the lines observed to be working. At the same time certain time-tested features are replaced to suite the convenience and emerging needs without seriously dwelling upon their impact. It was interesting to note that the multistoried structure at Guna, though built using similar architectural style, is more occupant-friendly with the roofs being sufficiently high. This structure however digresses from seismic safety norms and does not provide for shear walls. The Koti Banal architecture did not cater to 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 yrs BP, as is evident from the dating of the Guna structure.

Conclusion

The studies show that the people in the region have traditional knowledge and capability for constructing earthquake-safe structures and they could construct these almost 1000 yrs BP. The Koti Banal architecture that attained its zenith around 880 ± 90 yrs BP imbibes almost all earthquake safety measures and the performance of these structures has been certified by a number of earthquakes. This architecture might well have started after the earthquake of AD 1100, that is believed to have devastated large tracts across India.

This architecture needs to be studied and documented in more detail. Intricacies of this age-old construction style have the potential of unfolding a new line of construction that might be more effective for this terrain.

It is observed that many old structures in the Koti Banal style are being put to disuse and are deteriorating fast due to the lack of maintenance. People are demolishing these old structures so as to use the disassembled building material for construction of new and modern dwellings. The masses therefore need to be made aware about and educated on the issue of protecting these heritage structures.

Representatives of the Koti Banal architecture need to be protected as heritage buildings so as to enable the coming generations to have a glimpse of the architectural tradition of the region. This would also provide researchers with an opportunity to study this architectural style of Uttarakhand in detail.

1. Bilham, R., Gaur, V. K. and Molnar, P., Himalayan seismic hazard. *Science*, 2001, **293**, 1442–1444.
2. Feldl, N. and Bilham, R., Great Himalayan earthquakes and the Tibetan plateau, *Nature*, 2006, **444**, 165–170.
3. Thakur, V. C., Seismotectonics and earthquake geology aspects of northwestern Himalaya. *Geol. Surv. India Spec. Publ.*, 2006, **85**, 61–71.
4. *Vulnerability Atlas of India, Parts I to III*, Earthquake, Windstorm and Flood Hazard Maps and Damage Risk to Housing, Building Materials and Technology Promotion Council, New Delhi, 1997, p. 712.
5. Indian Standard: 4326, Indian standard code of practice for earthquake resistant design and construction of buildings, Second Revision, Bureau of Indian Standards, New Delhi, 1993.
6. FEMA 310, *Handbook for Seismic Evaluation of Buildings – A Prestandard*, American Society of Civil Engineers, 1998.
7. Mayes, R. L. and Naiem, F., *The Seismic Design Handbook* (ed. Naiem, F.), Kluwer, 2001, p. 735.
8. Deb, S. K., Seismic base isolation: An overview. *Curr. Sci.*, 2004, **87**, 1426–1430.
9. Indian Standard: 1893, Part 1, Criteria for earthquake resistant design of structures – General provisions and buildings, Bureau of Indian Standards, New Delhi, 2002.
10. Sweemey, S. C., Horney, M. A. and Orton, S. L., 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), 2004.
11. Koshihara, M. and Sakamoto, I., Seismic performance of wooden buildings in Japan. In Japan–Taiwan International Workshop on Urban Regeneration 2005, Maintenance and Green Material, Taipei, Taiwan, 23–27 November 2005, pp. 73–74.

ACKNOWLEDGEMENTS. Financial support for the study from the Disaster Risk Management Programme, Ministry of Home Affairs, Government of India, and United Nations Development Programme, India is acknowledged. We thank Shri N. S. Napalchyal, Principal Secretary, Disaster Management, Government of Uttarakhand, for support and encouragement and Dr C. M. Nautiyal, Birbal Sahni Institute of Palaeobotany, Lucknow for radiocarbon dating of the samples. We also thank the two anonymous referees for their critical comments that helped improve the manuscript.

Received 13 June 2007; revised accepted 8 July 2008