Seismic Vulnerability and Conservation Strategies for Lalitpur Minor Heritage

Dina D'Ayala

Abstract: *Nepal lies in a region of the world with one of the greatest seismic risks. Nepal's Kathmandu Valley is home to a very high concentration of unique architectural heritage in the three capitals of Kathmandu, Lalitpur, and Bhaktapur, where buildings dating to the thirteenth century form a consistent portion of the urban fabric. While studies on the seismic vulnerability of other elements of the built environment have been undertaken, especially on primary services such as schools and hospitals, very modest technical research on the seismic vulnerability of the historic architecture of this region and on suitable retrofitting techniques has been undertaken. The procedure described below follows a methodology developed for vulnerability assessment of historic urban city centers in Europe. The work entails:*

- *identification of the most common structural typologies, in terms of layout, structure, and agglomeration*
- *a census of existing traditional seismic-resilient features*
- *selection of a sample of buildings of each typology in a particular area of the urban center*

For the selected sample the following is carried out:

- *development of a tailored survey form*
- *street surveys aimed at identifying geometric and structural features*
- *analysis of the data based on plasticity theory and collapse mechanism to assess seismic vulnerability*
- *definition of damage scenarios*

On the basis of the results obtained, recommendations for repair and strengthening form the conclusions of this paper.

Introduction

This paper presents the seismic vulnerability analysis and possible strengthening strategies of local traditional houses in the city of Lalitpur, Kathmandu Valley, Nepal. This work was carried out within the ASIA-URBS NPL-3-05 Development Project sponsored by the European Aid and coordinated by UMEDP Lalitpur and the Chester City Council, UK (Urban Management and Economic Diversification Project 2004). Since the 1988 Nepal-India border earthquake, the awareness of seismic risk has grown greatly in Nepal. Risk analysis and earthquake scenarios have been produced for Nepal generally and for the Kathmandu Valley specifically (National Society for Earthquake Technology Nepal [NSET-Nepal]) (GeoHazards International 1999). This has been followed by studies on the seismic vulnerability of important public buildings, such as hospitals (Guragain, Pandey, and Shrestha 2004) and schools (Bothara et al. 2002; Bothara, Guragain, and Dixt 2002), and by the compilation of a building inventory of the Kathmandu Valley for seismic vulnerability purposes (Ohsumi et al. 2002).

Given the very high profile of the architectural heritage present in the Kathmandu Valley, and given the region's susceptibility to highly destructive earthquakes, great concern is voiced on the effects of a destructive earthquake on monumental buildings. Studies on specific typologies (Ranjitkar 2000; Shakya 2000) are producing an increasingly lively debate on the best ways to strengthen these buildings without affecting their architectural and historical value (Yeomans and Michelmore 2000). The preservation of entire urban blocks of traditional buildings, albeit of lesser individual value, is a problem of different scale and magnitude in terms both of developing awareness and of devising effective and sustainable policies. To date, no detailed analysis of the seismic vulnerability of ordinary residential historic buildings has been conducted in the Kathmandu Valley.

Traditional urban housing in developing countries has been substantially eroded in the past twenty years, owing to supposedly better and safer housing conditions offered by new typologies, such as reinforced concrete, infill-frame apartment blocks. Vernacular historic buildings fall prey not only to socioeconomic advancement but also to the lack of specifically developed analytical models that professionals can reliably use to evaluate the actual safety of these buildings with respect to seismic hazard. This phenomenon is common to many countries worldwide, notwithstanding the evidence of time—i.e., the fact that a vernacular building type might have survived many destructive events in the past.

In earthquake prone countries, vernacular architecture has typically evolved over centuries, with recurring construction details that testify to the viability of practices hundreds of years old that directly respond to the seismic hazard of these regions. These features, which enable ordinary buildings to withstand seismic shaking, were developed and modified through centuries of direct experience and observation of damage. Specifically, in regions of medium seismicity, the following features will typically be found: corner returns and quoins, connection with party walls, regular masonry fabric (stone or brickwork), floor and wall ties, and alternate orientation of floor structures. In regions of higher seismicity, the above features will be accompanied by others, such as timber ring beams, monolithic lintels and stone frames around openings, and framing and bracing of masonry with timber post and struts. Not all of these details were consciously developed to satisfy the demands earthquakes pose to structures, but it is likely that the observation of performance during shaking of buildings with and without certain features, and the recurrence of satisfactory seismic behavior, have resulted in a sort of natural selection.

In the present paper, a sample of buildings built with sun-dried and fired brickwork in part of the historic city center of Lalitpur is analyzed in detail. Specifically, the paper discusses the construction features that qualify these buildings' seismic behavior and presents the results of a limit state statistical vulnerability analysis, which provides a measure of the efficacy of the construction features highlighted above. The procedure adopted, Failure Mechanisms Identification and Vulnerability Evaluation (FaMIVE), follows a methodology developed for vulnerability assessment of historic urban city centers in Europe (D'Ayala et al. 1997; D'Ayala 1999; D'Ayala and Speranza 2002; D'Ayala and Speranza 2003). It is used to identify collapse mechanisms corresponding to specific construction features and to quantify the collapse load factor for each mechanism, so as to determine the level of shaking that will trigger a given behavior. Each building is given a vulnerability measure, and on the basis of the statistical distribution of it within the sample, fragility curves and damage scenarios are developed. From the results obtained, repair and strengthening recommendations are given, and they form the conclusions of this paper. The study was carried out within an EU-funded rehabilitation project (Urban Management and Economic Diversification Project 2004).

In order to understand the seismicity of Nepal, it is essential to study the earthquake sequence of the Himalayan region. A search on a catalogue of significant earthquakes from 1063 to 1984 (U.S. Geological Survey 2009) compiled from Indian sources (Tandon and Srivastava 1974; Chandra 1977; Rao and Rao 1984; Srivastava and Ramachandran 1985) reveals that at least 100 earthquakes with magnitudes between 5 and 8.25 on the Richter scale occurred in the period between 1816 and 1984 (excluding the 1980 earthquake) with epicenters within the borders of the Nepalese territory, while as many as 350 would have been felt in Nepal from neighboring regions during the same period. This count does not include the more recent earthquakes of 1980 and 1988 or the Gujarat earthquake of 2001. The records prior to 1816 are much more scattered; in the period between 1255 and 1816, there are records of only seven earthquakes at intervals of approximately 150 years, all highly destructive.

From a worldwide seismic hazard study that ran from 1992 to 1999, the Global Seismic Hazard Assessment Program (GSHAP), it is expected that peak ground accelerations as high as 3.2–4.8 m/sec.^{2} (10.50 × 15.75 ft./sec.^{2}) can have 10% probability of being exceeded in the next fifty years for the whole territory of Nepal (International Lithosphere Program 1999). These values equate to an earthquake with a maximum peak ground acceleration of 0.3–0.5 g. The eastern cluster of earthquake epicenters is located within the proximity of the Kathmandu Valley, which is also the most populous area of Nepal. Good accounts of the effects of at least two earthquakes are available for this area, the great Bihar-Nepal earthquake of 1934 (Brett 1935; Rana 1985) and the 1988 Udaypur Gahri earthquake. Extensive studies have been carried out on these two earthquakes, which often represent the basis for the development of future seismic scenarios for the Kathmandu Valley.

Choice and Description of the Sample

The sample chosen for the analysis is made up of the houses clustered around the Chyasal Square in Lalitpur, one of the three royal cities of the Kathmandu Valley. The neighborhood is particularly interesting for its layout and its mixture of buildings of different periods, with very different levels of maintenance, from the fifteenth century onward. A significant number of original buildings have been replaced by five-story, concrete-frame structures. This is very worrisome, not only in terms of the loss of original fabric but also in terms of the associated seismic risk that these buildings pose, given the very poor construction quality revealed during the visual survey. This, associated with their substantially greater height and their small footprint, identifies them as a very vulnerable type.

The traditional *newari* house is usually of a rectangular-shaped plan of about 6 m (19.7 ft.) in depth with facades of various widths, but most commonly between 4 m to 8 m (13.1 to 26.2 ft.) (Korn 1976; Guragain, Pandey, and Shrestha 2004). The organization of the house is vertical, over three stories, with a spine wall running the full height, creating front and back rooms. At the upper story, the spine wall is sometimes replaced by a timber-frame system, called *dalan*, so as to create a larger continuous space. The staircase is usually a single flight to one side of the plan. The bathroom, where present, is found at ground floor level, while the kitchen is on the top floor, usually directly under the roof as a fire prevention measure. Units are arranged in long rows or arrays around squares and common courtyards. The construction of each unit is usually independent, so that the facades are not continuous over party walls, but each unit forms a separate cell. However, the brickwork of the facade and the party wall are continuous and connected around the corner, providing a good connection between facades and sidewalls. The inherent seismic resilience of this construction type is proven by the high rate of survival from historic earthquakes, such as the great Bihar-Nepal earthquake of 1934 and the more recent 1988 Udaypur Gahri earthquake (Pandey and Molnar 1988).

Because of this system of construction, the growth of the block is not necessarily homogeneous, and adjacent plots are built at different times. Hence, each house is structurally independent, although there is virtually no gap between adjacent buildings. Until recently, due to the continuity of style and building practice, both layout and size of openings and level of floors were fairly homogeneous throughout. However, due to inheritance laws and customs, very often the property is split in equal parts among the male children, and the house is divided vertically by the introduction of party walls and new sets of stairs. In these cases the orthogonal wall is not usually connected to the facade and might run through the middle of a row of openings. Most interestingly, it appears that the two portions of the house are then further altered at different times and in different ways, according to the needs and wealth of the occupants, creating differences in floor levels, with substantial consequences for the structural behavior and hence the seismic vulnerability of the original unit.

Another typology of the same period is the *math*, or Hindu priest's house, also organized around a courtyard but with a different arrangement of spaces on different sides of the courtyard in relation to the owner's occupation. Normally the *math* is fully integrated into a terrace of houses along a street and may only be recognized by its superior wood carving and more extravagant decoration (Korn 1976).

Within the sample, there is also a minority of isolated buildings built during the late nineteenth and early twentieth centuries in the neoclassical *Rana* style. These buildings have the typology of Italianate palaces; they are usually of three stories with higher floor-to-ceiling heights and larger window openings. They do not have timber frames with long lintels around the openings, but they maintain the substantial roof overhangs and pegged floor construction.

Timber Pegs and Timber Bands

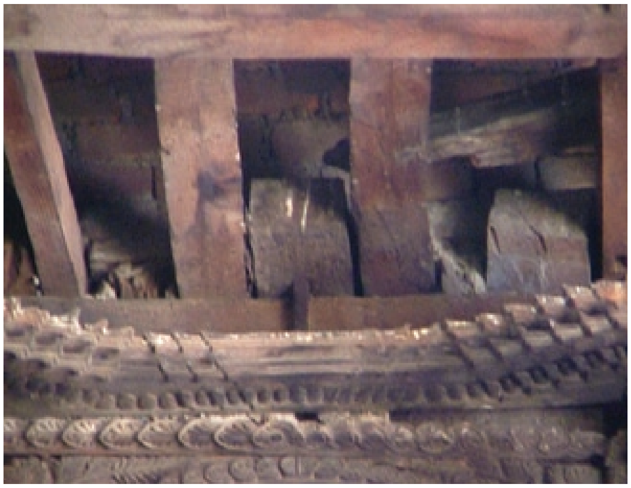
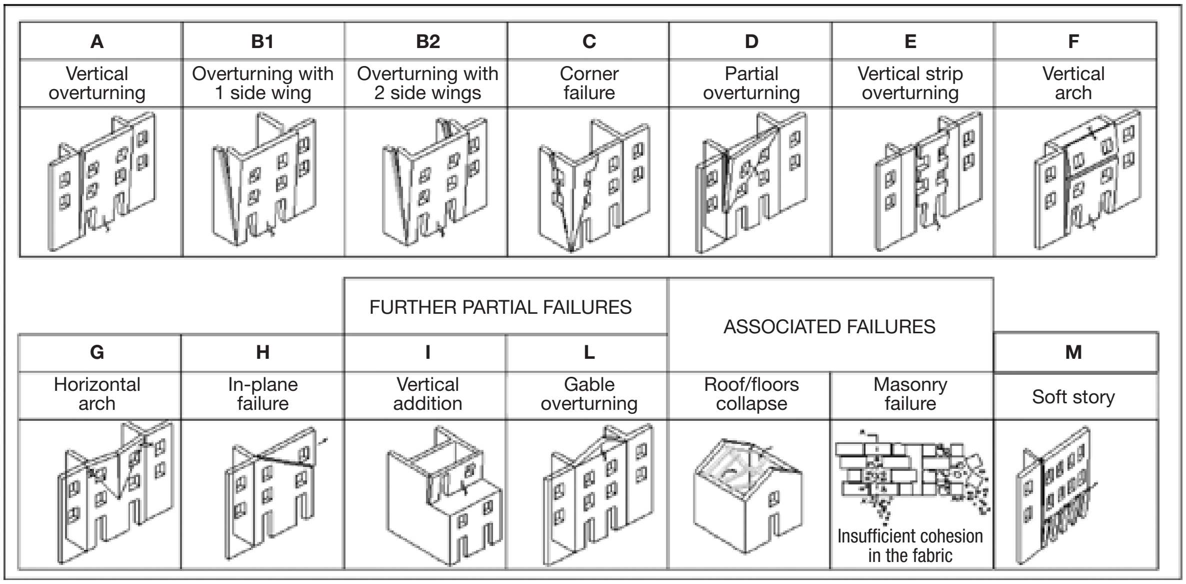


FIGURE 1 Timber pegs, or *chokus*.

A rather common feature of Nepalese traditional construction is the insertion of pegs, called *chokus*, to restrain floor joists from sliding over walls. Two vertical pegs are usually inserted through a joist on each side of the wall. Typically this will occur every two or three joists (fig. 1). From an external visual inspection, the *chokus* are easily identified at roof level, due to the presence of the overhang; however, they are also present at intermediate stories on joists passing over the internal wall. For the intermediate stories, the common practice is for the joists to be anchored with pegs on the internal face of the external wall and in between the two masonry leaves or wythes. This practice is very effective in preventing relative sliding of the floor structure on the walls in the presence of lateral forces and hence creates a box effect, while at the same time, given the flexibility of the pegs and their position, it does not prevent other movements associated with temperature and other environmental effects. The presence of the pegs is also effective in limiting any substantial out-of-plane movement of the external walls due to uneven settlements.

The presence of *chokus* at roof level means that the fundamental mechanism of the facade moves from free overturning (fig. 2, types A to E) to an arch effect (type F), in which the top of the wall is prevented from moving out of plane. From the histogram in figure 3, it can be noted that the majority of buildings with pegs at roof level (63%) have collapse load factors (the value of

FIGURE 2 Facade mechanisms of failure.



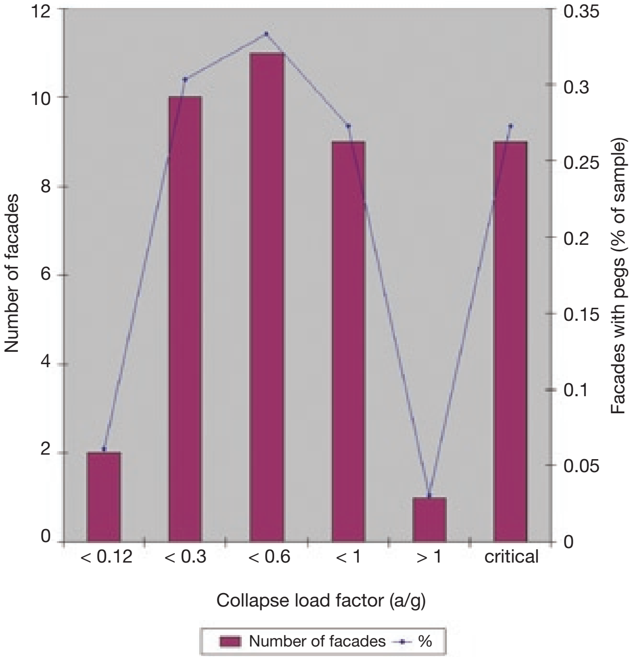


FIGURE 3 Occurrence of timber pegs (*chokus*) in the sample, and associated collapse load factor.

horizontal acceleration, *a*, as a proportion of *g*, which can be considered as the ultimate capacity of the facade) greater than 0.3 and that this mechanism is critical—i.e., it determines the vulnerability of the building, only for the 27% of the set with pegs, where the load factor is less than 0.3 (equivalent to 8.5% of the entire sample).

Most commonly, the pegs butt on a timber wall plate running along the width of the facade on which the joists sit. In most cases the timber wall plate is positioned directly above the level of the window frames, spanning the openings, and it runs the entire width of the facade (fig. 4).

While the best traditional practice uses wall plates on both masonry leaves or wythes of the facade, which are connected by transversal struts dovetailed into them, as can be seen in some of the oldest and better-built examples, nowadays the common practice is to use only one wall plate spanning over the internal masonry leaf or wythe of the wall.

From a structural point of view, the double wall plate is effective in redistributing the vertical loads more evenly across the wall; furthermore, in the original arrangement, it has the dual function of tying together the two masonry leaves or wythes of the wall and, in the presence of lateral load, preventing shear cracks in the masonry from running from one floor to the next.

A similar function is played by the timber bands included in the masonry at the mid-height of the wall within the masonry piers (fig. 4). Their presence is most effective when they run the entire length of the facade and continue around the corner, so as to form an effective ring beam that ties the orthogonal walls together. They are rather uncommon in the sample studied.

The Dalan

Among the many striking timber construction details of traditional buildings in the Kathmandu Valley, the *dalan* is certainly the most obvious and interesting in structural terms. The *dalan* is a timber frame made of twin wooden columns surmounted by a capital on which sits a double beam. The two adjacent timber frames are usually connected only at the level of the beam. The *dalan* is most commonly found at the ground floor of the main facade of buildings in which the front room is used as a shop or workshop. It is also common in upper stories as an internal structure in place of the spine wall. The columns usually have a square cross section of about 100 × 100 mm (3.9 × 3.9 in.) at the minimum and 150 × 150 mm (5.9 × 5.9 in.) at the maximum, and they are pinned to the ground 100–150 mm (3.9–5.9 in.) apart. The capital and the beam are also connected to the column by timber

FIGURE 4 Structure with timber bands at mid-height of the wall.

FIGURE 5 *Dalan* structure at the ground floor of a courtyard.

pins, and the joists of the floor above sit directly on the beam, connected to this in some cases by timber pegs. Therefore, the first-floor joists directly support the facade of the upper stories. The *dalan* usually spans the width of the building, with only small masonry piers of about 200 mm (7.8 in.) in width restraining it laterally and connecting it to the rest of the masonry structure.

In seismic terms, the *dalan* construction can be compared to a modern, concrete, soft-story structure and its associated failure mechanism, as all connections are simply pinned. The only lateral restraint, when present, is provided by the shear strength of the masonry piers at the edge of the facade. Figure 5 shows a well-preserved example of *dalan* in the internal courtyard of a *math* house, while figure 6 is an example of *dalan* walled in at a later stage to create more residential accommodation on the ground floor.

FIGURE 6 Original *dalan* structure walled in at a later time. Note that there is no external masonry pier adjacent to the external *dalan* column.

The histogram in figure 7 shows the range of collapse load factor associated with the *dalan*-type structure. None is greater than the reference design acceleration 0.32 g, provided by the Nepalese Seismic Code (Nepal 1995a; 1995c). In fact, the majority has a collapse load factor smaller than 0.15, and in 63% of facades with a *dalan*, the soft-story mechanism with lateral overturning becomes the critical element—i.e., the one yielding the highest value of vulnerability for the facade.

Opening Size and Window Frames

Window openings vary in size depending on the period of construction. Older buildings have generally smaller square windows with lintels extending well into the surrounding masonry. These are usually built with a double

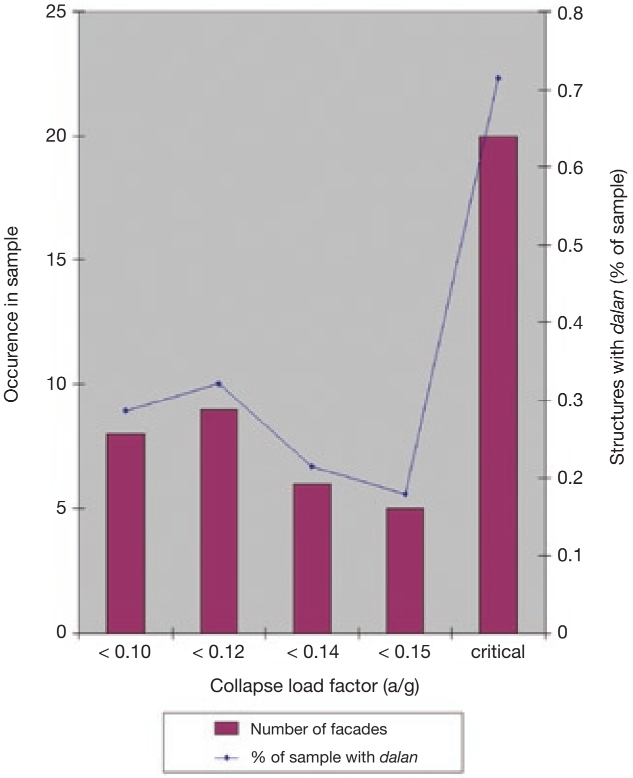


FIGURE 7 Statistical analysis of data characterizing the *dalan*.

FIGURE 8 Malla period (ca. 1200–1767) window.

FIGURE 9 *San Jhya* window.

frame, one within the external masonry leaf or wythe and a slightly larger one within the internal masonry leaf or wythe. The two frames are connected by timber elements embedded in the masonry (fig. 8). The size of the windows within a story may vary, depending on the use of the room.

A feature of older buildings is the *San Jhya* window (fig. 9), a richly decorated window that spans most of the facade at the third-story level with seating framed within it. Later buildings have more homogeneous openings; they are usually taller and narrower, of about 800 mm (31.2 in.) in width and extending almost from floor to floor (fig. 10). In this typology, spandrels above windows are very narrow. In more recent construction or alterations, the concept of the *San Jhya* has been extended to each floor, so that there is very little masonry left on the front facade of the house.

In more modern construction, window lintels are made of flat brickwork arches and, in a minority of cases, by stone frames (fig. 11). Traditionally the openings are

FIGURE 10 Full-height windows based on the *San Jhya* model.

FIGURE 11 Full-height windows with flat brickwork arches.

FIGURE 12 Full-width windows that do not leave sufficient width for the lateral pier.

placed at a fair distance from the facade's edges, leaving sufficient width for the lateral pier, constant throughout the full height of the building. This means that the pier can develop good structural behavior with substantial in-plane shear stiffness and, in turn, effective connection with lateral walls.

The increasing alteration of the openings, due to population overcrowding and internal subdivision of units, has led, as mentioned above, to a reduction in the width of lateral piers (fig. 12). The lateral capacity of the facade is hence reduced to the piers' flexural capacity, which is modest because of the poor tensile strength of the masonry.

Seismic Vulnerability Evaluation

In the present analysis, the seismic vulnerability (V) of each facade is evaluated based on the following formula (D'Ayala 1999):

$$V = \frac{d_i \, d_e}{ESC}$$

where *ESC,* the collapse load factor, is a function of the slenderness, the connection with other walls and floor structures, and the friction coefficient; d_e and d_i are two factors that are functions of the extension of the facade and floor structures involved in the collapse and the catastrophic character of the collapse, respectively.

Depending on the value of the product, four classes of seismic vulnerability are defined: low $V < 3.5$; medium, $3.5 < V < 7$; high, $7 < V < 15$; extreme, $V > 15$. These classes have proven to have good correlation with damage levels (D'Ayala 1999) for Modified Mercalli macroseismic intensity level (MMI) of VIII. This intensity level is especially significant, as it is defined as the level at which at least a quarter of masonry houses are seriously damaged. Although few collapse, many become uninhabitable.

According to the above division into four categories, a sample of 100 facades in Lalitpur was surveyed by a group of ten local architects and engineers supervised by the author over a period of two weeks in November 2002; 11.6% of the facades showed extreme vulnerability; 26.7%, high vulnerability; 50%, medium vulnerability; and 11.6%, low vulnerability (Urban Management and Economic Diversification Project 2004). This distribution also correlates well with the vulnerability classes A to C1 associated with the EMS '98 scale (Grünthal 1998; D'Ayala and Speranza 2002) and with their expected damage for macroseismic intensity (MMI) of VIII.

Although the boundaries between classes are represented by a deterministic value and hence by a line in figure 13, the transition between classes should be smooth, so that facades with values close to the boundary can be considered as belonging to either class. This is especially significant for facades with low-medium vulnerability.

In figure 14 the distribution of each mechanism in vulnerability classes is shown. The most common mechanism is the soft-story or *dalan*, mechanism type M, followed by the overturning of the facade, mechanism types D and A, and the collapse of the upper spandrel, mechanism type G (see fig. 2 for illustrations of facade mechanisms of failure). Figure 13 gives the same results plotted against the slenderness of the facade. The slenderness here is calculated as the ratio between the height of the facade and its average effective thickness. *Effective thickness* is defined as the geometric thickness reduced by a factor ranging between 0.05 and 0.15, depending on the level of maintenance of the facade and accounting for loss of mortar or brick due to decay.

The *dalan* mechanism is associated with the class of extreme vulnerability. This is because the mechanism is triggered by low levels of lateral acceleration, typically lower than 0.1 g; triggering of the mechanism leads to

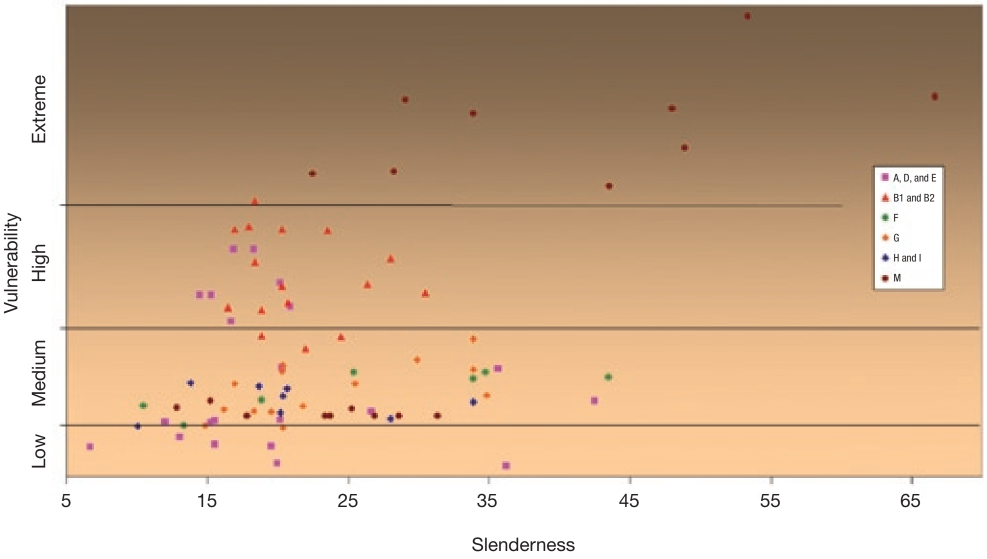


FIGURE 13 Distribution of failure mechanisms by slenderness and vulnerability classes (see fig. 2 for mechanisms of failure).

total collapse. However, the facades with highest vulnerability, those associated with high slenderness ratios, are affected by mechanism type D (overturning of the facade). These are very thin walled buildings of five stories, of which the lower two are original masonry and the upper three are concrete frame and infill masonry. These proved to be the most dangerous types of buildings in the sample.

Besides these, there is only one other case of extreme vulnerability. It is associated with a building with pegs but with a very poor level of maintenance, which fails by mechanism type F. These buildings show an average collapse load factor of 0.08 g, and they are likely to be damaged by an earthquake of MMI = VII.

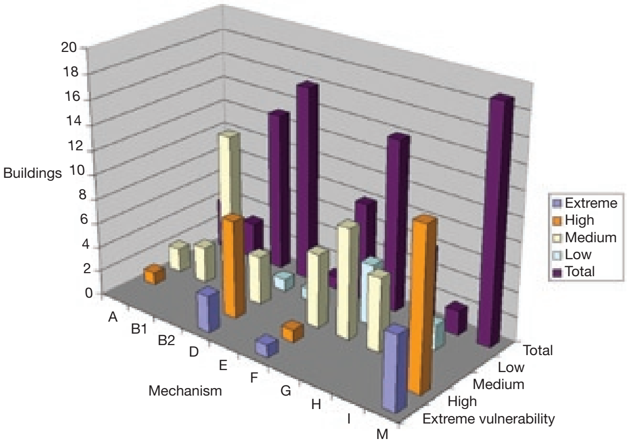


FIGURE 14 Distribution of failure mechanisms by class of vulnerability (see fig. 2 for mechanisms of failure).

Facades with high vulnerability are affected by either the *dalan* mechanism or by overturning of the facade, mechanisms A and D, when this is poorly connected to party walls. These are typically facades that do not have visible pegs at the roof level and hence do not benefit from the restraining action exerted by the horizontal structural elements. These buildings, with an average load factor of 0.11 g, are slightly more resilient than the previous class and will receive serious damage in an earthquake of intensity MMI = VIII.

The medium vulnerability class comprises facades affected by all types of mechanisms except the *dalan*. The most common type, however, is B2, overturning with party walls, occurring when there is good connection between the facade and the walls normal to it. As seen in figures 7 and 14, this mechanism has a weak correlation with slenderness, and the vulnerability range for this type is rather narrow. To this class also belong the majority of arch effect mechanisms, type F; this also provides the lower bound of vulnerability for facades with pegs. When facades have both pegs and good connections with party walls, the out-of-plane mechanism requires rather high accelerations to be triggered, and the in-plane mechanism takes place instead. This is the case of the facades failing with mechanism type H. It has been assumed that the diagonal cracks will run the whole height of the facade. In reality, where timber wall plates (wooden beams or tick planks rested upon and/or connected by pegs to the top of the wall on which the joists or rafters rest) are in place, the cracks will be confined to each story height, but this has been disregarded here in favor of safety. The average collapse load factor for these buildings is 0.30 g. They will survive an earthquake of intensity MMI = VIII with minor damage, and they will be seriously damaged by an event of intensity MMI = IX.

Also common within this class is mechanism type G—i.e., the failure of the upper spandrel of the facade between the lintels of the last row of windows and the roof structure. This mechanism is relatively common in this sample, as this strip of masonry is usually very narrow (it is made of few brick courses) and hence prone to collapse. Although the average collapse load factor is rather low, at 0.085 g, the extent of the facade involved is modest—hence the medium level of vulnerability.

Finally, to the class of low vulnerability belong otherwise well-built facades that are characterized by partial failure, either of the upper stories of the facade (types D or A), of the vertical addition (type I), or of the spandrel above the last row of windows (type G). This is particularly common in this sample.

To summarize, the vulnerability analysis shows that buildings with *dalan*-type construction are extremely vulnerable unless there is appropriate masonry restraint to the sides of the *dalan* structure. The construction details of the *dalan* need to be studied more closely, in order to identify better constraint conditions that might possibly reduce the vulnerability calculated so far. Given the present assumptions, all these facades need to be strengthened.

Facades with poor lateral connections and no visible presence of pegs are highly vulnerable, as the full height of the wall is prone to overturning and involves the floor structure in the collapse. In order to prevent this, as the reinstatement of the connection with the party walls is a difficult intervention, the recommended action would be to reintroduce *chokus* at the roof and possibly also at the floor levels. This would consistently reduce the vulnerability from high to medium. Facades with basically good construction standards—such as good maintenance of the masonry accompanied by connection to party walls and the presence of *chokus* at the roof level—all show medium-low levels of vulnerability and collapse load factors in the range of 0.20 to 0.50 g, depending on slenderness ratios and maintenance. Facades with localized defects, such as narrow upper spandrels, or connections only on one side or only at the lower levels, fail by mechanism types G and D respectively, with a collapse load factor of about 0.10 g, and they show the value of vulnerability in the upper range of the medium class. The behavior of these facades can partially improve if in the analysis, the effect of wall plates is accounted for. If these prove to be insufficient, then reinstatement of the *chokus* and connection at the sides by means of ties might provide the solution.

Finally, the analysis shows that well-built buildings will have high collapse load factors associated with global collapse mechanisms, typically in the range of 0.40–0.60 g, while the partial failure of upper spandrels or vertical later additions would occur for acceleration typically in the range of 0.20–0.30 g. These, however, would not create major damage or threat to life.

It is worth noting that all assumptions made have been made in favor of safety, while taking into account the level of reliability of the available data. In reality, some of the buildings in the sample might turn out to be more resilient than shown here.

Damage Scenarios

Damage scenarios for the houses surveyed used the same data as used in the design of new structures in the Kathmandu Valley. To properly quantify the type and extent of damage and hence best identify the strengthening strategies that would be most effective in reducing such damage, the following steps were taken with reference to the sample of houses surveyed.

First, fragility curves have been developed for the four most recurring structural typologies identified: facades with *dalan*, facades with *chokus* or with connections to lateral walls, facades with both *dalan* and *chokus*, and facades without *chokus* or connection to lateral walls. Second, it has been assumed that the extent of damage can be described and quantified by the six-level scale defined in Grünthal (1998). Third, the number of buildings in the sample in each damage state for a given level of design acceleration has been calculated.

In figure 15 the curves of cumulative distribution for each damage state are plotted against different levels of expected ground acceleration. These curves show the

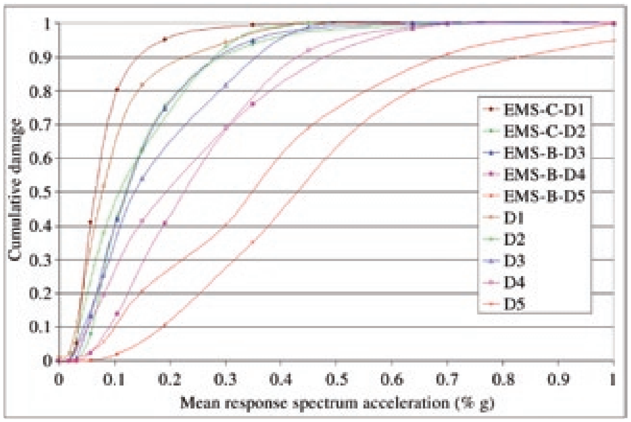


FIGURE 15 Cumulative damage distributions for values of peak ground acceleration (EMS = European macroseismic scale; D = damage level).

percentage of the building sample that would reach or overcome a given state of damage. Of particular interest to the present discussion are the values of the curves in correspondence to 0.32 g (seismic acceleration), corresponding to the level of design acceleration for new masonry structures prescribed in section 2.4 of the Nepalese code (Nepal 1995b). In correspondence to this value, figure 15 shows that more than 90% of the buildings will be damaged, and 80% will have at least slight damage, as characterized by table 1. About 62% of the buildings will suffer heavy damage, level D3; 35% will experience partial collapse, D4; and 11% will collapse, D5 (Grünthal 1998).

Most important, if the level of peak ground acceleration expected for a 50-year-return period is considered (i.e., g = 0.4, as explained earlier), it emerges from the diagram that at least 20% of the buildings will collapse, 45% will undergo partial collapse, up to 70% will be seriously damaged, and only 5% will survive unscathed.

These results highlight the urgency of adequate implementation of strengthening intervention, in order to substantially reduce the expected damage discussed above.

Conclusion

The following points emerge from the study of the seismic vulnerability of historic buildings in the Kathmandu Valley:

- From historic and seismological evidence, a destructive event can be expected with a return period of approximately 80 to 100 years in the Kathmandu Valley. According to the Global Seismic Hazard Assessment Program (GSHAP) study, an event with a return period of 50 years would be characterized by peak ground acceleration in the range of 0.40–0.48 g.
- Earthquake scenarios developed by other authors, taking as reference an event with characteristics similar to those of the 1934 earthquake, show that seismic vulnerability at an urban level has increased in the last 50 years, and that the death toll and destruction

Table 1 Definition of damage levels (after Grünthal 1998)

Damage level	Mean damage ratio	Damage type	Description of physical extent
D0	0.00	Undamaged	No visible
D1	0.05	Slight damage	Hairline cracks
D2	0.20	Moderate damage	Cracks 5–20 mm
D3	0.50	Heavy damage	Cracks > 20 mm or heavy damage to structural walls
D4	0.90	Partial collapse	Collapse of individual wall or individual roof support
D5	1.00	Collapse	More than one wall collapsed or more than half of roof

in the Kathmandu Valley would possibly be greater than those recorded for the 1934 event.

- A number of national documents prepared by the National Society for Earthquake Technology Nepal (NSET-Nepal), but not yet ratified as law, are available for the design of new masonry buildings in earthquake prone areas. These documents assume a maximum value of 0.32 g as design acceleration for masonry buildings, lower than the one suggested by the GSHAP study. These documents are also rather useful, as they indicate with diagrams and sketches correct construction and repair techniques and details. However, they often do not take into account conservation principles, such as minimal disturbance to the original fabric, in-kind repairs, and use of the same materials.
- The analysis of the architectonic and construction typologies in Kathmandu has identified three types of building agglomerations: buildings in straight arrays or rows, buildings around courtyards, and some hybrids. Two principal masonry typologies have been identified, one built with sun-dried bricks and one with fired traditional bricks (*dachi aapa*). The traditional floor plan typology is made up of closely spaced timber joists covered by floorboards with mud and, in a minority of cases, tiles. Alterations of the original floor structure are usually weakly reinforced flat concrete slabs.
- Numerous traditional details have been identified, most importantly the *dalan* structure, with crucial structural properties. Other structural features that make the traditional buildings seismically resilient have been identified as the *chokus* restraining the roof and floor structure within the masonry, the timber wall plates and timber bands, and the traditional design of the timber lintels. Among the features that constitute seismic weaknesses, it is important to point out that the jetty (the projecting part of a building) is present in 20% of the sample, and that 86% of the roofs have overhanging portions. Of this 86%, 33% are concrete slabs either flat or sloping.
- In order to quantify the seismic vulnerability of the sample, the Failure Mechanisms Identification and Vulnerability Evaluation (FaMIVE) procedure has been applied to all surveyed facades, identifying for each the crucial collapse mechanisms and its associated collapse load factor and vulnerability class. The overturning of the facade, either complete or partial, has an occurrence of 23% in the sample; followed by the *dalan* mechanism, with an occurrence of 22%; the overturning of the facade with side walls in 18.5%; the failure of the upper spandrel with 16%; followed by 9% of failure by arch effect; and a minority of in-plane failure. According to the classification of seismic vulnerability in four categories, in Lalitpur's sample, 11.6% of the facades show extreme vulnerability, 26.7% high vulnerability, 50.0% medium vulnerability, and 11.6% low vulnerability.
- Fragility curves for the sample have been developed in order to forecast levels and types of damage associated with different levels of seismic input. The results show that, in the event of a seismic input of the same level as the one considered by the Nepalese code of practice, 90% of the buildings will be damaged, and 80% will exhibit damage level of at least D2. About 62% of the buildings will suffer heavy damage, level D3; 35% will undergo partial collapse, D4; and 11% will collapse, D5. However, if the level of peak ground acceleration expected for a 50-year-return period is considered (i.e., g = 0.4), it can be seen that at least 20% of the buildings will collapse, 45% will undergo partial collapse, up to 70% will be seriously damaged, and only 5% will survive without damage.

The results summarized above show the necessity for a strategic policy of strengthening that will safeguard the historic character of the buildings of the Chyasal District, while at the same time improving their seismic performance. While the design specifics for each building should be defined upon the results of more detailed analyses, based on a thorough survey of each case, some general guidelines can be drafted based upon the results obtained:

- Buildings with *dalan*, especially in the case of those with small lateral masonry piers, need to be strengthened to prevent the soft-story mechanism. This occurs at very low values of the collapse load factor, and it is catastrophic, as it leads to complete collapse of the walls and floor structure above. The strengthening strategy needs to prevent the lateral overturning of the *dalan* columns. It was not possible during the visit to inspect the connection between the columns and the ground floor structure and foundation; this probably needs to be strengthened to prevent rotation. The connection with the timber beams supporting the masonry above would probably need to be strengthened, too. This can be achieved in both cases by introducing flitch plates within the existing timber structure. An alternative to this, if there is sufficient lateral space, is to build lateral masonry piers and connect these to the upper masonry.
- For buildings for which facade overturning will take place, it is first necessary to inspect more accurately the level of connection with party or other internal perpendicular walls. If this is lacking, it should be checked to see whether the horizontal structures provide sufficient restraint. If this is also lacking and the floor structures are of timber, then *chokus* should be introduced or reinstated, both externally at roof level and internally at lower levels. This will reduce the vulnerability level from high to medium and low.
- The analysis also proves that the level of maintenance is a crucial factor to the performance of these buildings. Hence, repointing and replacement of decayed masonry should be the first treatment for all buildings in the sample. In order to reduce the decay of the masonry, it is essential to use lime or mud mortar, avoiding the use of stabilizers or cements that can cause chemical attack on the sun-dried bricks. It is also advisable to restore and maintain in all buildings the overhang of the roof, as this shelters the masonry from direct rainfall.
- The most vulnerable buildings have proven to be those with additions of two or three stories in concrete above a slender masonry structure. Although this phenomenon is relatively limited in Chyasal, it is becoming increasingly common in many of the historical districts of the Kathmandu Valley. Short of demolishing these buildings, it is very difficult to envision effective ways of improving their seismic performance. As it is unlikely that demolition (which might also cause damage to adjacent buildings) will be pursued, more should be done to prevent the proliferation of these additions.
- The upper spandrels, between the lintels of the last row of windows and the roof structure, have proven to be vulnerable to low-level acceleration. Although this failure is localized, it can cause collapse of the roof and death in the street below; hence it should be prevented. The spandrels' behavior can be improved by consistent introduction of wall plates and timber bands at this level, and by connecting them vertically to the row of lintels below.

The application of the FaMIVE method to a sample of buildings in Lalitpur presented in this paper represents the first attempt to consistently apply the concept of seismic vulnerability assessment, as developed in literature for existing engineered buildings, to the historic architectural heritage of the Kathmandu Valley. By a thorough analysis of the construction details, buildings have been classified in typologies and vulnerability classes. For each typology, a fragility curve was created, relating to the type of collapse mechanism that develops. This type of analysis, which directly relates construction to seismic vulnerability, also allows the identification of the most suitable strengthening strategies to reduce the seismic risk of this urban agglomerate while preserving and enhancing the use of local historic characteristics.

The study has also emphasized that the greatest threat to the preservation of the historic environment and the greatest seismic risk are posed by uncontrolled urban development, as characterized by refurbishments of internal layouts and additions of stories. These alterations are carried out with materials extraneous to the building tradition—reinforced concrete, lightweight fired bricks, and corrugated steel sheets—and techniques that are borrowed from the modern construction industry without the necessary engineering knowledge and quality control.

References

Bothara, J. K., A. M. Dixit, M. Nakarmi, S. B. Pradanang, and R. C. Thapa. 2002. Seismic safety of schools in Kathmandu Valley, Nepal: Problems and opportunities. In *New Zealand Society for Earthquake Engineering Inc Technical Conference and AGM, War Memorial Centre, Napier, Friday/Sunday 15–17 March 2002: Conference Technical Papers.* Lower Hutt, N.Z.: New Zealand Society for Earthquake Engineering.

Bothara, Jitendra Kumar, Ramesh Guragain, and Arnod Dixt. 2002. *Protection of Educational Buildings Against Earthquakes: A Manual for Designers and Builders*. Kathmandu: National Society for Earthquake Technology, Nepal.

Brett, William Bailie. 1935. *A Report on the Bihar Earthquake and on the Measures Taken in Consequence Thereof up to the 31st December 1934*. Bihar, India: Superintendent, Government Print [India].

Chandra, Umesh. 1977. Earthquakes of Peninsula India: A seismotectonic study. *Bulletin of the Seismological Society of America* 67 (5): 1387–413.

D'Ayala, D. F. 1999. Correlation of seismic vulnerability and damage between classes of buildings: Churches and houses. In *Seismic Damage to Masonry Buildings: Proceedings of the International Workshop on Measures of Seismic Damage to Masonry Buildings: Monselice, Padova, Italy, 25–26 June, 1998,* ed. Alberto Bernardini, 41–58. Rotterdam: A. A. Balkema.

D'Ayala, Dina, Robin Spence, Carlos Oliveira, and Antonios Pomonis. 1997. Earthquake loss estimation for Europe's Historic Town Centres. *Earthquake Spectra: The Professional Journal of the Earthquake Engineering Research Institute* 13 (4): 773–93.

D'Ayala, D., and E. Speranza. 2002. An integrated procedure for the assessment of seismic vulnerability of historic buildings. In *The Twelfth European Conference on Earthquake Engineering, 9–13 September 2002, Barbicon Centre, London, UK,* 470. Oxford: Elsevier. http://people.bath.ac.uk/absdfda/ar561D'Ayala.PDF.

———. 2003. Definition of collapse mechanisms and seismic vulnerability of historic masonry buildings. *Earthquake Spectra: The Professional Journal of the Earthquake Engineering Research Institute* 19 (3): 479–509.

GeoHazards International. 1999. Loss estimation of the Bihar-Nepal earthquake and Kathmandu earthquake scenario. http://www.geohaz.org/contents/projects/kathmanduscenario.html.

Grünthal, Gottfried, ed. 1998. *European Macroseismic Scale 1998: EMS-98*. Cahiers du Centre Européen de Géodynamique et de Séismologie 15. Luxembourg: European Seismological Commission, Subcommission on Engineering Seismology, Working Group Macroseismic Scales.

Guragain, Ramesh, Bishnu Hari Pandey, and Surya Narayan Shrestha. 2004. *Guidelines for Seismic Vulnerability Assessment of Hospitals in Nepal*. Kathmandu: National Society for Earthquake Technology, Nepal. http://www.nset.org.np/nset/html/publication/pdfFiles/Guideline-vulnerablity%20assessment%20of%20Hospital.pdf.

International Lithosphere Program. 1999. Global Seismic Hazard Assessment Program. http://www.seismo.ethz.ch/GSHAP/.

Korn, Wolfgang. 1976. *The Traditional Architecture of the Kathmandu Valley*. Bibliotheca Himalayica, ser. 3, vol. 11. Kathmandu: Ratna Pustak Bhandar.

Nepal. His Majesty's Government of Nepal, Ministry of Housing and Physical Planning, Department of Buildings. 1995a. *Nepal National Building Code: NBC 105: 1994 Seismic Design of Buildings in Nepal*. Kathmandu: His Majesty's Government of Nepal, Ministry of Housing and Physical Planning, Department of Buildings.

———. 1995b. *Nepal National Building Code: NBC 202 1994: Mandatory Rules of Thumb: Load Bearing Masonry*. Kathmandu: His Majesty's Government of Nepal, Ministry of Housing and Physical Planning, Department of Buildings.

———. 1995c. *Nepal National Building Code: NBC 203 1994: Guidelines for Earthquake Resistant Building Construction: Low Strength Masonry*. Kathmandu: His Majesty's Government of Nepal, Ministry of Housing and Physical Planning, Department of Buildings.

Ohsumi, T., F. Kaneko, A. Dixit, and H. Fujitani. 2002. A building inventory of the Kathmandu Valley for vulnerability analysis and disaster mitigation planning. In *Proceedings of the Japan Earthquake Engineering Symposium* 11:2231–36. Japan: [Nihon Jishin Kogaku Shimpojumu?].

Pandey, M. R., and P. Molnar. 1988. The distribution of intensity of Bihar-Nepal earthquake of 15 January 1934 and bounds on the extent of the rupture zone. *Journal of Nepal Geological Society* 5 (1): 22–44.

Rana, Brahmasamsera Jangabahadura. 1985 [1935]. *Nepalako mahabhukampa, 1990 sala*. [Kathmandu]: Sahayogi Presa.

Ranjitkar, Rohit K. 2000. Seismic strengthening of the Nepalese pagoda: Progress report. In *Earthquake-Safe: Lessons to Be Learned from Traditional Construction: International Conference on the Seismic Performance of Traditional*

Buildings: Istanbul, Turkey, Nov. 16–18, 2000. Istanbul: ICOMOS International Wood Committee. http://www.icomos.org/iiwc/seismic/Ranjitkan.pdf.

Rao, B. Ramalingeswara, and P. Sitapathi Rao. 1984. Historical seismicity of Peninsular India. *Bulletin of the Seismological Society of America* 74 (6): 2519–33.

Shakya, Naresh Man. 2000. Temples and buildings standing over Kathmandu Valley, which is vulnerable to earthquakes. In *Earthquake-Safe: Lessons to Be Learned from Traditional Construction. International Conference on the Seismic Performance of Traditional Buildings: Istanbul, Turkey, Nov. 16–18, 2000.* Istanbul: ICOMOS International Wood Committee. http://www.icomos.org/iiwc/seismic/Shakya.pdf.

Srivastava, H. N., and K. Ramachandran. 1985. New catalogue of earthquakes for Peninsular India during 1839–1900. *Mausam* 36 (3): 351–58.

Tandon, A. N., and H. N. Srivastava. 1974. Earthquake occurrence in India. In *Earthquake Engineering: Jai Krishna Sixtieth Birth Anniversary Commemoration Volume,* ed. Jai Krishna and Anand S. Arya, 1–48. Meerut, India: Sarita Prakashan.

United States Geological Survey. 2009. Earthquake Hazards Program: Historic worldwide earthquakes: India. http://earthquake.usgs.gov/regional/world/historical_country.php#india.

Urban Management and Economic Diversification Project. 2004. *Prioritising the Cultural Heritage: Urban Management and Economic Diversification in the Sub Metropolitan City of Lalitpur and the Village Development Area of Khokana, Kingdom of Nepal*. Chester, UK: Chester City Council.

Yeomans, D. T., and D. Michelmore. 2000. Conserving the traditional buildings of the Kathmandu Valley. In *Cities and Sustainability: Sustaining Our Cultural Heritage,* ed. P. S. Brandon, P. Lombardi, and R. S. Perera, 6–16. Moratuwa, Sri Lanka: University of Moratuwa.