World Housing Encyclopedia

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HOUSING REPORT
Dry stone construction in Himachal Pradesh

Report #	172
Report Date	03-08-2013
Country	INDIA
Housing Type	Stone Masonry House
Housing Sub-Type	Stone Masonry House: Rubble stone without mortar
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Summary

The addressed building type has been identified in Himachal Pradesh, a northern state in India. It is a relatively recent construction typology, which can be seen prevalent in the areas where people have been forced to leave their traditional construction practices due to scarcity of wood. Thus, this construction style is nothing but the traditional housing style omitting the wooden elements, be it Kath-Kunni style of the Kullu, Shimla or Kinnaur districts or Thathara style of Chamba district. Due to the region's heavy precipitation both in terms of rainfall (June to July) as well as snowfall (October to March), rubble stones are preferred over the alternative locally available construction material, i.e. mud. However, these buildings possess high seismic vulnerability due to low in-plane and out-of-plane strength of their dry stone walls. This report identifies the main sources of seismic vulnerability of dry stone buildings and also suggests a retrofitting scheme to reduce the seismic vulnerability of such buildings.

1. General Information

Buildings of this construction type can be found in the North Indian state Himachal Pradesh, more specifically in the villages of the districts Chamba, Shimla, Kullu and Kinnaur of (**Figure 2**). This construction typology is the result of the vast availability of river stones and the scarcity of wood, which has forced people to leave their traditional construction techniques, like Thathara or Kath-kunni, and adopt this variant. There is no local name prevalent for this building type and these are generally referred to as 'pattharkemakan' (houses of stone).

This type of housing construction is commonly found in both rural and sub-urban areas.

This is a relatively recent construction practice and dates back no longer than around fifty years.

This type of construction is currently still being constructed and is prevalent in some areas of Himachal Pradesh.

Figure 1. Dry stone house (top) and another structure with more informal construction of the same typology (bottom).

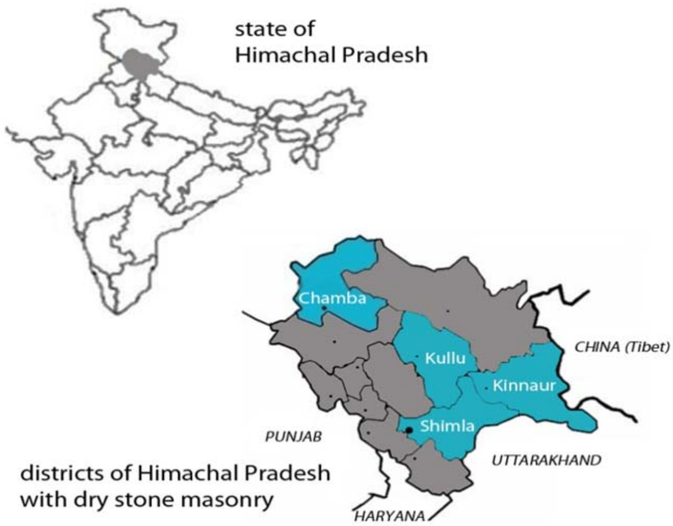

Figure 2. Districts in Himachal Pradesh where this typology can be found.

2. Architectural Aspects

2.1 Siting

These buildings are typically found in sloped and hilly terrain. They do not share common walls with adjacent buildings. The distance from a neighboring building can be as small as 30 cm but is generally 3 meters (typical street width). The land available is contoured in almost all the cases. Therefore, depending upon the slope of the site, a flat base platform is prepared in the following two ways: (a) in case of sites with steep slope, usable flat land is created by constructing a dry stone gravity retaining wall over which the building is erected; (b) in case of a site with a comparatively gentle slope, cut-and-fill technique is used, which enables a small usable piece of land in the lower level (which is usually used as shelter for cattle or as storage space) and a larger usable space at the upper level (**Figure 3**). When separated from adjacent buildings, the typical distance from a neighboring building is 3 meters.

2.2 Building Configuration

The houses are generally rectangular or L-shaped in plan with a verandah in the front. Upper floors also have verandahs. A typical house is of two to three storeys. Large-size openings are usually provided in walls (**Figure 4**) for ventilation. Sometimes, in order to have cupboards in the walls, small niches are left at place and bricks are used in that portion (**Figure 5** and **Figure 6**) to create a space within the wall as the thickness of the single wythe brick wall is much smaller than the thickness of the dry stone wall. Horizontal partitions are made within the so created niche, using wooden planks or RC slabs. The cupboard is usually kept open, but may be covered sometimes, using a wooden frame and panels.

2.3 Functional Planning

The main function of this building typology is single-family house. In a typical building of this type, there are no elevators and no fire-protected exit staircases. The typical building has one or two more doors other than the main door, which can be counted as the escape routes at the rear. In case of more than one storey, an RC or wooden staircase is usually provided outside the building.

2.4 Modification to Building

Buildings of the addressed type are usually constructed with original plans, and no significant modifications to the existing structures have been observed during the survey. However, in some cases, the construction is done in stages, i.e. the ground storey is constructed first and another storey is added later when funds are available.

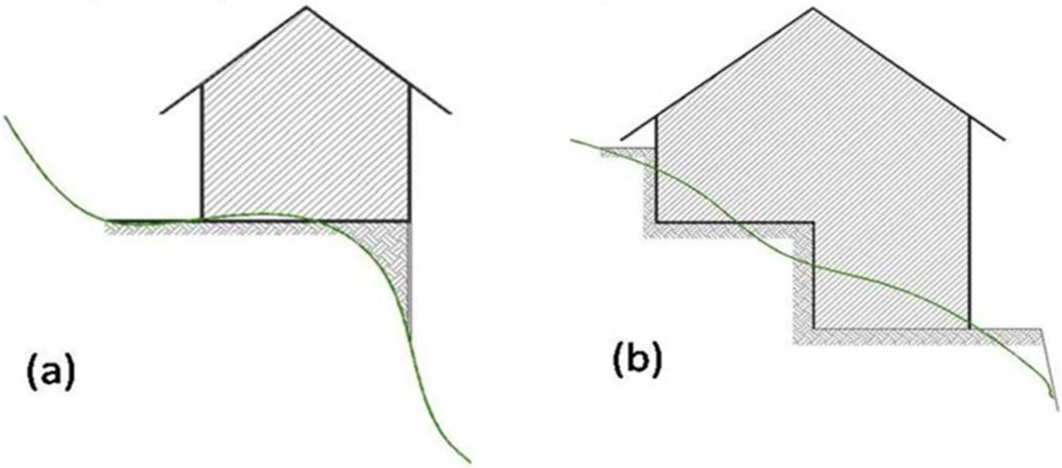

Figure 3. (a) Site development on (a) a steep slope, and (b) on a gradual slope.

Figure 4. Large opening in wall for light and ventilation purpose.

Figure 5. Use of bricks to accommodate cupboards at the inside of the wall.

Figure 6. Niche for cupboard seen from inside.

Figure 7. A dry stone structure with RC flat slab under construction. RC columns are additionally used to support the longer span.

3. Structural Details

3.1 Structural System

Material	Type of Load-Bearing Structure	#	Subtypes	Most appropriate type
Masonry	Stone Masonry Walls	1	Rubble stone (field stone) in mud/lime mortar or without mortar (usually with timber roof)	☑
		2	Dressed stone masonry (in lime/cement mortar)	☐
	Adobe/ Earthen Walls	3	Mud walls	☐
		4	Mud walls with horizontal wood elements	☐
		5	Adobe block walls	☐
		6	Rammed earth/Pise construction	☐
	Unreinforced masonry walls	7	Brick masonry in mud/lime mortar	☐
		8	Brick masonry in mud/lime mortar with vertical posts	☐
		9	Brick masonry in lime/cement mortar	☐
		10	Concrete block masonry in cement mortar	☐
	Confined masonry	11	Clay brick/tile masonry, with wooden posts and beams	☐
		12	Clay brick masonry, with concrete posts/tie columns and beams	☐
		13	Concrete blocks, tie columns and beams	☐
	Reinforced masonry	14	Stone masonry in cement mortar	☐
		15	Clay brick masonry in cement mortar	☐
		16	Concrete block masonry in cement mortar	☐
Structural concrete	Moment resisting frame	17	Flat slab structure	☐
		18	Designed for gravity loads only, with URM infill walls	☐
		19	Designed for seismic effects, with URM infill walls	☐
		20	Designed for seismic effects, with structural infill walls	☐
		21	Dual system – Frame with shear wall	☐
	Structural wall	22	Moment frame with in-situ shear walls	☐
		23	Moment frame with precast shear walls	☐
	Precast concrete	24	Moment frame	☐
		25	Prestressed moment frame with shear walls	☐
		26	Large panel precast walls	☐
		27	Shear wall structure with walls cast-in-situ	☐
		28	Shear wall structure with precast wall panel structure	☐
Steel	Moment-resisting frame	29	With brick masonry partitions	☐
		30	With cast in-situ concrete walls	☐
		31	With lightweight partitions	☐
	Braced frame	32	Concentric connections in all panels	☐
		33	Eccentric connections in a few panels	☐
	Structural wall	34	Bolted plate	☐
		35	Welded plate	☐

Material	Type of Load-Bearing Structure	#	Subtypes	Most appropriate type
Timber	Load-bearing timber frame	36	Thatch	☐
		37	Walls with bamboo/reed mesh and post (Wattle and Daub)	☐
		38	Masonry with horizontal beams/planks at intermediate levels	☐
		39	Post and beam frame (no special connections)	☐
		40	Wood frame (with special connections)	☐
		41	Stud-wall frame with plywood/gypsum board sheathing	☐
		42	Wooden panel walls	☐
Other	Seismic protection systems	43	Building protected with base-isolation systems	☐
		44	Building protected with seismic dampers	☐
	Hybrid systems	45	other (described below)	☐

3.2 Gravity Load-Resisting System

The vertical load-resisting system is stone masonry walls. The buildings mostly consist of flat RC roof and floors, sometimes with beams. Sloping wooden roofs with stone slates or galvanized iron (G.I.) sheets are the other common type. The floors and roof transfer the gravity load to 500 mm thick walls made of undressed river stones without mortar. In some cases RC columns are also added to support longer span beams (**Figure 7**). However, these supporting RC columns are non-engineered elements, and their dimensions as well as reinforcement detailing vary ad hoc, depending on the judgment of the mason. Since masons are empirically familiar with the high axial loads and the carrying capacity of RC columns, very slender columns (with e.g. cross-sections dimension 200-250 mm) are common. Due to high slenderness, low reinforcement, and poor joint detailing, these columns are equally vulnerable to earthquake loads, as the dry stone walls are.

3.3 Lateral Load-Resisting System

The lateral load-resisting system is stone masonry walls. The building's total lateral load resistance is provided by the same dry stone walls (up to 500 mm thick) made of undressed river stones without mortar, whose initial purpose was to support the gravity loads. The reinforced-concrete slabs provided for roof and floors provide some lateral restraint to the walls in out-of-plane action. However, due to random rubble dry stone construction, the walls have very little in-plane and out-of-plane resistance.

3.4 Building Dimensions

The typical plan dimensions of these buildings are: lengths between 8 and 12 meters, and widths between 5 and 8 meters. The building has 2 to 3 storeys. The typical span of the roofing/flooring system is 5 meters. The typical storey height in such buildings is 2.5 meters. The typical structural wall density is more than 20 % (i.e. ratio of total area of walls in both directions to the floor area).

3.5 Floor and Roof System

Material	Description of floor/roof system	Most appropriate floor	Most appropriate roof
Masonry	Vaulted	☐	☐
	Composite system of concrete joists and masonry panels	☐	☐
Structural concrete	Solid slabs (cast-in-place)	☑	☐
	Waffle slabs (cast-in-place)	☐	☐
	Flat slabs (cast-in-place)	☐	☐
	Precast joist system	☐	☐
	Hollow core slab (precast)	☐	☐
	Solid slabs (precast)	☐	☐
	Beams and planks (precast) with concrete topping (cast-in-situ)	☐	☐

Material	Description of floor/roof system	Most appropriate floor	Most appropriate roof
	Slabs (post-tensioned)	☐	☐
Steel	Composite steel deck with concrete slab (cast-in-situ)	☐	☐
Timber	Rammed earth with ballast and concrete or plaster finishing	☐	☐
	Wood planks or beams with ballast and concrete or plaster finishing	☐	☐
	Thatched roof supported on wood purlins	☐	☐
	Wood shingle roof	☐	☐
	Wood planks or beams that support clay tiles	☐	☐
	Wood planks or beams supporting natural stones slates	☐	☐
	Wood planks or beams that support slate, metal, asbestos-cement or plastic corrugated sheets or tiles	☐	☐
	Wood plank, plywood or manufactured wood panels on joists supported by beams or walls	☐	☐
Other	Described below	☑	☑

The buildings mostly have solid RC slabs (115 to 150 mm thick) that are manually cast in-situ without any compaction equipment. The concrete mix is also prepared manually with poor control on mix proportions and water content. The RC slabs are usually bearing on the full thickness of the walls, but no additional reinforcement is provided along the walls. The roofs are generally sloping with timber rafters and GI sheeting or wood shingles for cladding. Depending on the local availability, stone slates are also used for roof cladding. The sloping roofs are generally without cross-bracing and ties, making them prone to damage during earthquake. Due to dry stone construction of walls, anchorage of roofs to the walls is generally not observed. Flat RC roofs have also been observed in some buildings, which are expected to slightly improve the seismic behavior of buildings due to their in-plane rigidity and good bearing on the walls.

3.6 Foundation

Type	Description	Most appropriate type
Shallow foundation	Wall or column embedded in soil, without footing	☐
	Rubble stone, fieldstone isolated footing	☐
	Rubble stone, fieldstone strip footing	☑
	Reinforced-concrete isolated footing	☐
	Reinforced-concrete strip footing	☐
	Mat foundation	☐
	No foundation	☐
Deep foundation	Reinforced-concrete bearing piles	☐
	Reinforced-concrete skin friction piles	☐
	Steel bearing piles	☐
	Steel skin friction piles	☐
	Wood piles	☐
	Cast-in-place concrete piers	☐
	Caissons	☐
Other	Described below	☐

The foundations consist of hand packing of stones of different shapes and sizes without any mortar. The foundation depth ranges from 900 mm for loose soil to 200 mm for hard strata up to the ground level. The foundation is usually of the same width as the wall above (i.e. 500 mm). The plinth level of the house is about 300 mm above the ground level (**Figure 8** and **Figure 9**). Sometimes, dry stone retaining walls are used to support the backfill or create a flat platform to support the building (**Figure 3**).

Figure 8. Raised plinth of a house can be seen in the front.

Figure 9. Plinth level of a house under construction.

4. Socio-Economic Aspects

4.1 Number of Housing Units and Inhabitants

Each building typically has 1 housing unit. The number of inhabitants in a building during the day or business hours is less than 5. The number of inhabitants during the evening and night is 5-10.

4.2 Patterns of Occupancy

These houses have generally one verandah in the front, one living room, two bed rooms, a kitchen and a toilet. The arrangement of spaces varies from house to house.

4.3 Economic Level of Inhabitants

Income class	Most appropriate type
a) very low-income class (very poor)	☐
b) low-income class (poor)	☑
c) middle-income class	☑
d) high-income class (rich)	☐

Ratio of housing unit price to annual income	Most appropriate type
5:1 or worse	☑
4:1	☐
3:1	☐
1:1 or better	☐

What is a typical source of financing for buildings of this type?	Most appropriate type
Owner financed	☑
Personal savings	☑
Informal network: friends and relatives	☑
Small lending institutions / micro-finance institutions	☐
Commercial banks/mortgages	☐
Employers	☐
Investment pools	☐
Government-owned housing	☐
Combination (explain below)	☐
other (explain below)	☐

In each housing unit, there are 1 bathroom without toilet, 1 toilet only and no bathroom including toilet.

4.4 Ownership

The type of ownership or occupancy is individual ownership.

Type of ownership oroccupancy?	Most appropriate type
Renting	☐
Outright ownership	☐
Ownership with debt (mortgage or other)	☐
Individual ownership	☑
Ownership by a group or pool ofpersons	☐
Long-term lease	☐
other (explain below)	☐

5. Seismic Vulnerability

5.1 Structural and Architectural Features

Structural/ Architectural Feature	Statement	Most appropriate type		
		True	False	N/A
Lateral load path	The structure contains a complete load path for seismic force effects from any horizontal direction that serves to transfer inertial forces from the building to the foundation.	☐	☑	☐
Building Configuration	The building is regular with regards to both the plan and the elevation.	☑	☐	☐
Roof construction	The roof diaphragm is considered to be rigid and it is expected that the roof structure will maintain its integrity, i.e. shape and form, during an earthquake of intensity expected in this area.	☐	☑	☐
Floor construction	The floor diaphragm(s) are considered to be rigid and it is expected that the floor structure(s) will maintain its integrity during an earthquake of intensity expected in this area.	☑	☐	☐
Foundation performance	There is no evidence of excessive foundation movement (e.g. settlement) that would affect the integrity or performance of the structure in an earthquake.	☑	☐	☐
Wall and frame structures - redundancy	The number of lines of walls or frames in each principal direction is greater than or equal to 2.	☑	☐	☐
Wall proportions	Height-to-thickness ratio of the shear walls at each floor level is: Less than 25 (concrete walls); Less than 30 (reinforced masonry walls); Less than 13 (unreinforced masonry walls);	☑	☐	☐
Foundation-wall connection	Vertical load-bearing elements (columns, walls) are attached to the foundations; concrete columns and walls are doweled into the foundation.	☐	☑	☐
Wall-roof connections	Exterior walls are anchored for out-of-plane seismic effects at each diaphragm level with metal anchors or straps	☐	☑	☐
Wall openings	The total width of door and window openings in a wall is: For brick masonry construction in cement mortar : less than ½ of the distance between the adjacent cross walls; For adobe masonry, stone masonry and brick masonry in mud mortar: less than 1/3 of the distance between the adjacent cross walls; For precast concrete wall structures: less than 3/4 of the length of a perimeter wall.	☑	☐	☐
Quality of building materials	Quality of building materials is considered to be adequate per the requirements of national codes and standards (an estimate).	☐	☑	☐
Quality of workmanship	Quality of workmanship (based on visual inspection of few typical buildings) is considered to be good (per local construction standards).	☐	☑	☐
Maintenance	Buildings of this type are generally well maintained and there are no visible signs of deterioration of building elements (concrete, steel, timber)	☑	☐	☐
Additional Comments	The buildings may appear to have good seismic features from the above table, as the walls are thick and regularly placed in both the directions of the building. But due to the dry stone construction feature, the walls have very poor resistance in both in-plane as well as out-of-plane direction. This makes the building highly vulnerable for lateral forces.			

5.2 Seismic Features

Structural Element	Seismic Deficiency	Earthquake Resilient Features	Earthquake Damage Patterns
Wall	Very low in-plane and out-of-plane capacity to resist lateral loads. Integrity with cross-walls and roof/floor diaphragms is also poor.	Longer stones integrating the two wythes are provided at regular interval acting as through (connecting) stones avoiding splitting of the walls under shaking.	No record of performance during past earthquakes is available, but the walls are expected to collapse due to out-of-plane bending.
Roof and floors	The roofs are generally sloping timber constructions, without any bracing and anchorage with the walls, rendering it to act as a flexible and extremely vulnerable component.	The floors are generally solid RC slabs, acting as rigid diaphragms.	Different members of the sloping roof are expected to undergo large relative movement, eventually causing collapse of the roof.
Foundation	The foundation also consists of dry stones, hand packed into a trench. This renders a poor support to the walls at foundation.		The foundation is not able to provide resistance to the walls against sliding and out-of-plane bending. The walls are expected to collapse in out-of-plane action.

The main cause of high seismic vulnerability of these buildings is the poor shear and bending strength of the wall construction materials. The vulnerability is further increased due to sloping roof without any bracing, no anchorage of the walls at floor and roof level, and inadequate support by the foundations. The dry stone walls are expected to split and collapse in out-of-plane action, even under nominal seismic shaking.

5.3 Overall Seismic Vulnerability Rating

The overall rating of the seismic vulnerability of the housing type is *A: HIGH VULNERABILITY (i.e., very poor seismic performance)*, the lower bound (i.e., the worst possible) is A: HIGH VULNERABILITY (i.e., very poor seismic performance), and the upper bound (i.e., the best possible) is *A: HIGH VULNERABILITY (i.e., very poor seismic performance)*.

Vulnerability	High	medium-high	medium	medium-low	low	very low
	very poor	poor	moderate	good	very good	excellent
Vulnerability Class	A	B	C	D	E	F
	☑	☐	☐	☐	☐	☐

5.4 History of Past Earthquakes

Date	Epicenter, region	Magnitude	Max. Intensity
1555	Kashmir	> Mw 7.0	
1720	Kumaun	> M 8.0	
1803	Garwhal	Mw 8.09	
1855	Shrinigar (Kashmir)	Mw 6.3	
1905	Kangra (Himachal Pradesh)	Mw 7.8	IX
1974	Pattan	Mw 6.2	
1981	Karakoram, Darel, Tangir, Khanbari valleys	M 6.2	
1991	Uttarkashi (Uttarakhand)	Mw 6.8, mb 6.1 (IMD), Ms 7.1 (USGS)	I (MMI) = VIII
1999	Chamoli (Gharwal region)	Mw 6.4, Ms 6.6, ml 6.8 (IMD), mb 6.3 (USGS)	I (MMI) = VIII
2005	Muzzafarabad (Kashmir)	Mw 7.6	X to XII

6. Construction

6.1 Building Materials

Structural element	Building material	Characteristic strength	Mix proportions/ dimensions	Comments
Walls	River stones (Metamorhic stones of different types)	Not possible to measure or estimate	--	No experimental means have been developed yet to quantify strength of such materials.
Foundation	River stones	Not possible to measure or estimate	--	No experimental means have been developed yet to quantify strength of such materials.
Frames (beams &columns)	NA	--	--	--
Roof and floor(s)	RC for floor and Wooden (locally available cedar) or steel trusses for roof	Concrete 15 MPa Reinforcement 415 MPa Structural Steel 250 MPa	Typical Concrete Mix – 1:2:4	The concrete is prepared manually without any mechanical mixer or vibrating (compacting) equipment. Hence, the expected quality is poor.

6.2 Builder

Construction is carried out by local artisans under the surveillance of the owner himself. Sometimes the building owner and family members also work for construction, with or without hiring the services of a local artisan.

6.3 Construction Process, Problems and Phasing

Wall system: The stone walls are load bearing with a thickness of 500 mm and a height of 2.5 m. Both external and internal walls are of the same thickness. Construction material: Walls are made of locally available undressed stones of varying sizes, packed together without any mortar (**Figure 10**). Sometimes the size of a single stone is large enough to cover the entire opening as a lintel beam, otherwise RC or timber members are used. Kail or deodar wood is used for frames and panels of doors and windows. Construction methodology of walls: Step 1. Stones of an average size of 300x150x150 mm are laid in courses over the plinth level up to a 2.5 m height creating a 500 mm wide wall. These stones are packed tightly together using small stone chips. Longer (through) stones covering the entire thickness of wall and connecting the withes are used at regular intervals. Step 2. A wooden or concrete beam is placed horizontally at lintel level, i.e. at 2.5 m height (which is also the roof level) to support the roof or floor above (**Figure 11**). In case of a wooden beam, it is directly placed over the wall without any connection to the wall. Step 3. Walls are plastered with mud on the inner side and finished with mud and cow dung slurry. The exterior side of walls is generally left exposed (**Figure 12**).

Floor system: Materials used for the floors and ceilings are stones, mud and timber. All materials are locally available. Construction methodology: Ground floor: In order to construct the ground floor, stones are laid onto the ground up to a height which is little lesser than the plinth level. Earthen material is added over these stones and rammed until it attains a thickness of 50 mm. The final finish is of mud and cow dung slurry. Other floors: For constructing the other floors, secondary wooden beams of 100x150 mm are placed at a distance of 450 mm centre to centre onto the main wooden beams (**Figure 13**). Wooden planks of 20x250 mm are then nailed to these members, which are later plastered with mud. In the recent construction, RC flat slabs are more common for upper floors. Roof system: As the area receives rain in monsoon and heavy snow in winters, the houses have sloping roofs, i.e. gable or hipped roofs where the gradient of the slope is slightly reduced over the verandah so as to create sufficient head room (**Figure 14**). Roofs are covered with slate stones which are locally available while deodar or kail wood is used for beams, rafters and purlins. In some recent constructions, steel trusses are also being used. Construction methodology: (1) Hipped roofs: Step 1. A wooden beam of cross section 200x150 mm is placed over the wall without any connection. Step 2. A-type frames are nailed on top of this wooden beam in order to have a hipped roof profile (**Figure 15**). These A-type frames support a number of purlins of the size 90x120 mm which are nailed to them. The gap between two adjacent purlins is equivalent to the size of the slates above. The slates are nailed as roof covering material on top of the purlins. Sizes of slates are generally 6x12", 7x14", 8x16", 9x18", and 10x20”. (2) Gable-end roofs: In case of gable roof, a ridge beam is directly placed over the stone masonry gable ends (**Figure 16**). This ridge beam can either be a tree stem or a hewn member of cross section 200x150 mm. Rafters of the size 120x150 mm run over and nailed to the ridge beam at one end and wall plate (a wooden plank with generally no anchorage/connection with the wall) at the other end. Purlins of the size 90x120 mm are nailed to these rafters where the distance between two adjacent purlins is equal to the size of the slates. Slates are nailed as roof covering material on top of the purlins (**Figure 17**). Sizes of slates are generally 6x12", 7x14", 8x16", 9x18", or 10x20".

The construction of this type of housing takes place in a single phase.

Typically, the building is originally designed for its final constructed size.

6.4 Design and Construction Expertise

Dry stone houses are constructed by local masons who generally possess little engineering knowledge but who are able to master the work. They generally hail from families of traditional masons who used to construct vernacular houses. The owner of the house also helps in the construction process. Architects and engineers have no role in the design or construction of this housing type.

6.5 Building Codes and Standards

This construction type is not addressed by the codes/standards of the country.

6.6 Building Permits and Development Control Rules

This type of construction is a non-engineered, and authorized as per development control rules. Building permits are not required to build a house in this region.

6.7 Building Maintenance

Typically, the building of this housing type is maintained by Owner(s). Since the building materials (stones, and to some extent wood) are highly durable against the effects of weather, the structure is innately durable and thus requires little maintenance. The walls from inside are finished with a coat of mud and cow dung slurry, which is repeated once per year. No other significant maintenance is required.

6.8 Construction Economics

It is difficult to determine the exact cost of construction as the price of construction material is highly varying at different locations, depending on the distance from the source. For instance, the price of stones varies from Rs 1 to Rs 14 per stone; cost of sand, which is used for preparing the RC slabs, varies from Rs 10 to Rs 80 per cubic meter.

Figure 10. A house under construction illustrating the width of the walls as well as the varying sized stones.

Figure 11. Wooden beam at lintel/floor level.

Figure 12. A house showing its exposed exterior and plastered interior.

Figure 13. Secondary wooden members resting on the main wooden beam in order to construct the first floor.

Figure 14. View of village Rakh, in Chamba district with a variety of dry stone masonry houses; gable-end roof, hipped roof and roof-changing-angle over verandah can be seen.

Figure 15. A-type frame of a hipped roof.

Figure 16. Gable-end roof where wooden planks have been used as gable infill.

Figure 17. Slates nailed to the roof purlin.

7. Insurance

Earthquake insurance for this construction type is typically unavailable. For seismically strengthened existing buildings or new buildings incorporating seismically resilient features, an insurance premium discount or more complete coverage is unavailable.

8. Strengthening

8.1 Description of Seismic Strengthening Provisions

Strengthening of Existing Construction:

Seismic Deficiency	Description of Seismic Strengthening provisions used
Low in-plane and out-of-plane strength of dry stone walls	The walls can be strengthened using ferro-cement (a layer of welded wire mesh grid sandwiched between two layers of cement-sand mortar or micro-concrete), applied on both faces of the dry stone walls, properly interconnected with the wall. The composite action of the stone wall and ferro-cement is expected to provide adequate in-plane as well as out-of-plane strength. The steel connectors provided at regular intervals to interconnect the two layers of reinforcement on opposite faces of the wall will prevent the splitting of the dry stone walls.
Flexible roof/floor system	The flexible roof and floor can be strengthened using diagonal bracings, properly nailed/bolted to the roof/floor members (**Figure 18** and **Figure 19**). The diagonal bracing is expected to enhance the integrity of the roof/floor system, and at the same time to provide lateral restraint to the walls.
Lack of lateral support to walls	External band (ties) can be provided at roof level (and also at floor level in case of flexible floor diaphragms) to provide out-of-plane support to the walls. The bands may be provided in timber, steel or RC and have to be continuous on all internal and external walls.
Lack of anchorage of roof beam and rafters with walls	For existing construction, the ridge beam and rafters are simply placed on the walls without any positive anchorage. This will cause relative movement of these elements with respect to the walls, leading to the collapse of the roof. Therefore, these elements should be properly anchored to the walls. In the proposed strengthening scheme this can be achieved by using metallic connectors nailed with the wooden members and anchored into the ferro-cement layer or the roof/floor band.

Strengthening of New Construction:

Seismic Deficiency	Description of Seismic Strengthening provisions used
Low in-plane and out-of-plane strength of dry stone walls	The main vulnerability issue in this type of construction is the low shear and bending strength of dry stone walls. This construction has evolved from the traditional Kath-Kunni (Rautela *et al.,* 2009) construction in which extensive use of wooden members is made in the dry stone walls, to provide shear and bending strength. As the timber has become scarce in these areas, it is not possible to return the past construction practices. An alternative to the same can be using cement-sand mortar and providing horizontal layers of reinforcement (preferable in the form of galvanized welded wire mesh to avoid corrosion) at a vertical gap of about 600 mm. These horizontal layers of reinforcement will serve four purposes: (i) the shear strength of the wall will increase enhancing their in-plane capacity against lateral loads, (ii) the out-of-plane strength of walls will be enhanced due to composite action of the wire mesh with the stone walls, (iii) splitting of the walls under shaking will be avoided, and (iv) overlapping wire mesh at corners and junctions will enhance the integrity with cross walls.
Flexible roof/floor system	The flexible roof and floor are to be provided with diagonal bracings (IS 13827: 1993).
Lack of lateral support to walls	RC bands are to be provided at roof and floor levels to provide lateral support to walls. In case of RC floors, there is no need to provide a band at floor level.
Lack of anchorage of roof beam and rafters with walls	The roof members are to be anchored into the RC roof band using steel plates/bolts.

8.2 Seismic Strengthening Adopted

Has seismic strengthening described in the above table been performed in design and construction practice, and if so, to what extent?

No case of strengthening of such buildings was observed during an extensive survey of the study area.

8.3 Construction and Performance of Seismic Strengthening

Was the construction inspected in the same manner as the new construction?

The strengthening measures suggested above are own ideas of the authors, originated from the retrofitting measures used in case of other low-strength building constructions (IS 13828 : 1993, IS 13935 : 2009). The same (or any other strengthening measures) have not been observed in practice and therefore information about their performance during an actual earthquake is not available.

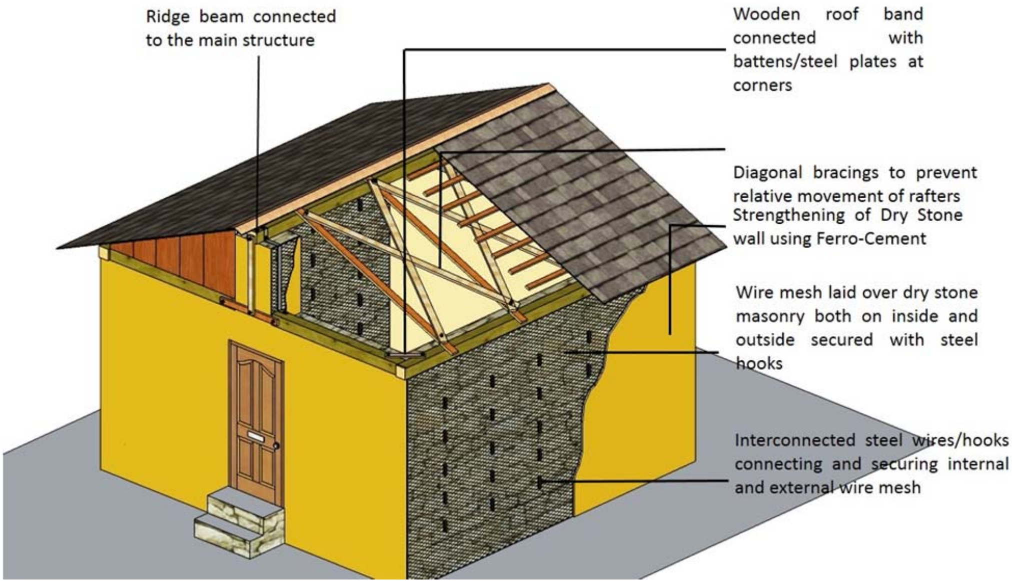

Figure 18. Retrofitting measures for dry stone houses.

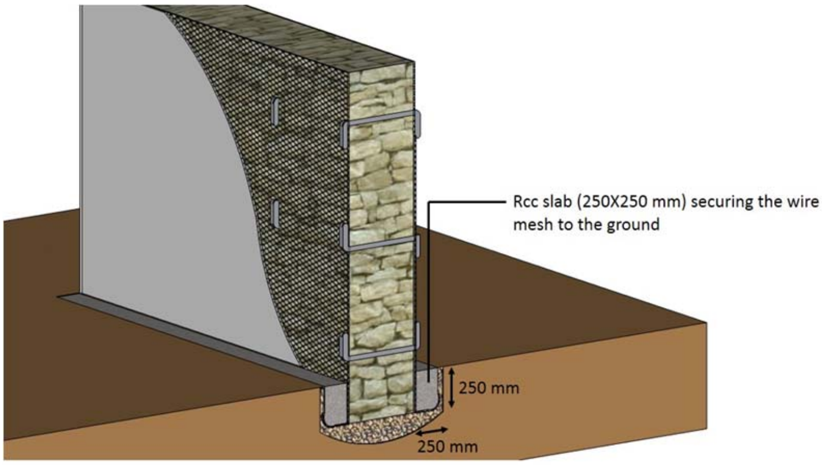

Figure 19. Wall section

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