



2015 Project for International Contribution to Cultural Heritage Protection

Project for Investigation of Damage Situation of Cultural Heritage in Nepal

Structural Survey of Historic Buildings

October 2016

Tokyo National Research Institute for Cultural Properties

2015 Project for International Contribution to Cultural Heritage Protection:
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Structural Survey of Historic Buildings

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Preface

This report is the result of an investigation of cultural heritage damage caused by the Gorkha Earthquake on 25 April 2015. The project was commissioned by the Agency for Cultural Affairs and implemented by the Tokyo National Research Institute for Cultural Properties (TNRICP).

In this project, investigations were conducted from comprehensive viewpoints including architectural history, building structure, urban design, conservation and preservation, and intangible cultural heritage by researchers from Nippon Institute of Technology, the University of Tokyo, Kagawa University, Tokyo Metropolitan University, Tohoku Institute of Technology, and TNRICP, as well as outside experts in cultural heritage conservation.

This volume is the result of "Structural Survey of Historic Buildings" conducted at Jaganath Temple and Gopinath Temple, which are representative multi-tiered towers (*Mandir*), in Hanuman Dhoka Durbar Square that was inscribed on the World Heritage List.

Masahiko Tomoda

Head of Conservation Design Section

Japan Center for International Cooperation in Conservation

Tokyo National Research Institute for Cultural Properties

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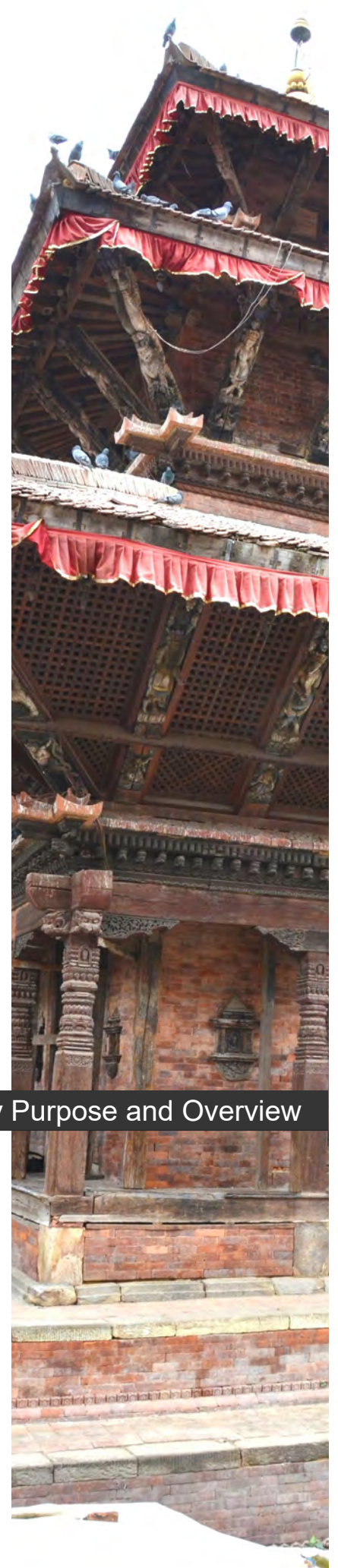
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Appendix : The structural drawings of Jagannath and Gopinath Temples

Attached DVD: Results of Micro-tremor measurement

A.1 - A.16 Jagannath Temple

A.17- A.36 Gopinnath Temple



1. Survey Purpose and Overview

1. Purpose and Overview of the Survey

The devastation caused by the Gorkha Earthquake in Nepal was characterized to some extent in prior surveys by various researchers. Referring to information obtained in these prior surveys, this structural survey focused on identifying earthquake weaknesses in Nepal's traditional buildings, which have mainly mixed structures comprised of brick and timber. Both observation and technical analysis techniques were used. Among the multi-tiered towers (Pagoda, *Mandir*), which is one of representative type of historical buildings, Jagannath and Gopinath temples were selected for detailed survey as a typical example of devastation. Selected buildings were measured and scaled drawings were created. Details regarding the point and extent of devastation and the stability and materials (brick and timber) of the building structure were carefully recorded. Results from this survey should contribute to preservation and restoration planning.

On the occasion of the field survey, we performed micro-tremor measurement and survey on the situation of devastation, with the surveys on construction system and building materials, in order to obtain the information for verifying the structural performance of subject buildings by more accurate structural analysis model. The selected area of 3D measurement and an example of measurement results are shown in Fig.1-1 and Fig.1-2.

The survey period, primary activities, and participating investigators were as follows:

Survey periods: 24–31 November 2015 3D and micro-tremor measurements

24–28 December 2015 Building and material survey

Investigators: Koshihara Laboratory, Institute of Industrial Science, the University of Tokyo

Takiyama Laboratory, Tokyo Metropolitan University

Miyamoto Laboratory, Kagawa University

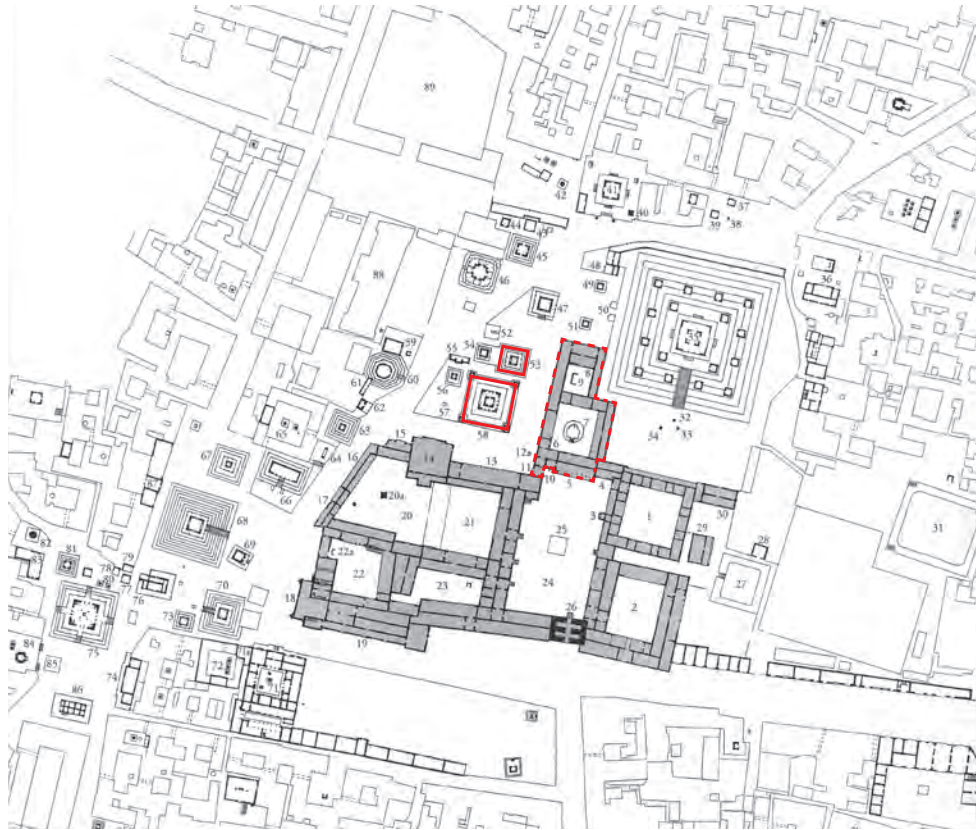


Fig.1-1 The selected area for 3D measurement (Red line)(The area inside dotted line includes the rooms that have not researched yet.)(Quoted from Niels Gutschow, *ARCHITECTURE OF THE NEWARS: A History of Building Typologies and Details in Nepal, Volume II The Malla Period*, Serindia Publications, Chicago, 2011, p.344 and retouched by the editor.)



Fig.1-2 The selected area for 3D measurement depicted using actual survey results



2. Detailed Building Survey

2. Detailed Building Survey

The Multi-tiered tower is a common architectural style in Nepal's temples. For understanding its features, a detailed survey was conducted at Jagannath and Gopinath Temples that are multi-tiered towers and suffered typical damage from the Gorkha Earthquake.

2.1. Jagannath Temple

The building description of Jagannath Temple and proposed repairs by 「John Sanday, *KATHMANUDU VALLEY: Nepalese historic monuments in need of preservation*, Unesco, 1982」 are followings.

Jagannath: B/K-174

(Two-tiered temple)

Location: Hanuman Dhoka

Constructed: First half of seventeenth century

Renovated: 1938 and 1968

Deity: Vishnu

Religion: Vaishnava

Records: 1633 and 1654

Building description

The temple, which is located just outside the main palace gate at Hanuman Dhoka, is considered to be one of the best examples in this style. The broad square sanctum base has threefold doorway openings on all four sides. The intricately carved struts supporting the two roofs display figures from the Hindu pantheon; at their base are some good samples of erotica. The carving on the doors and windows is also of good quality. The brickwork beneath many layers of paint is the traditional Telia brick. At each corner of the upper podium are small two-tiered shrines of similar design. On the eastern face of the pedestal there is an inscription of Pratap Malla in praise of the goddess Bhawani written in fourteen different scripts. The temple was built during the reign of King Lakshminarasimha Malla.

Proposed repairs

This is a temple of great importance needing careful cleaning, repair and conservation. Over the years it has collected several layers of paint and dirt, marring its architectural beauty. A major repair programme will be necessary. It is likely that some structural consolidation and repair will be required to the roofs. The roof covering as well as the carvings will require proper chemical treatment.

For the Jagannath Temple, structural drawings that included each storey's the framing plan of each storey and elevation, an X-Y cross section, brick details, and more were created from the detailed survey. The basic dimensions of the building and section were also recorded. Table2-1-1 shows the list of the structural drawings.

Tab.2-1-1 The list of the structural drawings (Jagannath Temple)

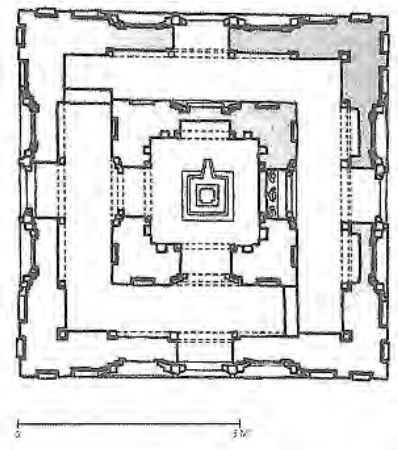
Number	Name of the drawings	Scale	Note
1	Floor plan of pillars and wall, 1st storey	1 : 100	
2	Plan of struts of the 1st tier and joists, 2nd storey	1 : 100	Position of knee brace in 2nd storey
3	Plan of rafters of the 1st tier	1 : 100	Position of rafter in 2nd storey
4	Plan of struts of the 2nd tier and joists, 3rd storey	1 : 100	Position of knee brace in 3rd storey
5	Plan of ridge beams, 3rd storey	1 : 100	Position of girder in 3rd storey
6	Plan of rafters of the 2nd tier	1 : 100	Position of rafter in 3rd floor
7	North elevation	1 : 100	Keeping the horizontal of 3D scan data
8	East elevation	1 : 100	Keeping the horizontal of 3D scan data
9	West elevation	1 : 100	Keeping the horizontal of 3D scan data
10	South elevation	1 : 100	Keeping the horizontal of 3D scan data
11	Section of X (NS) direction	1 : 100	Drawing podium as horizontal
12	Section of Y (EW) direction	1 : 100	Drawing podium as horizontal
13	Size of bricks	1:10	

<Structure>

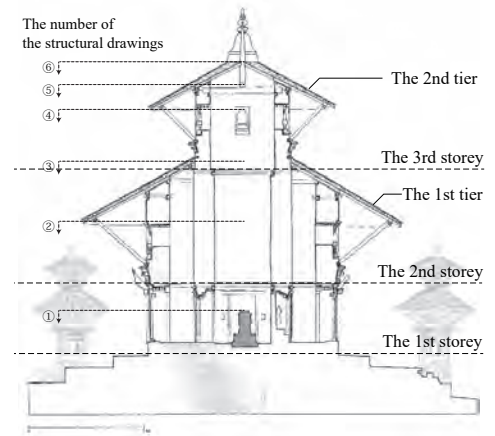
Plan of the first storey and section of Jagannath temple are shown in Fig.2-1-1.

There are brickwork walls at outer and inner of the first storey. The dimension of bricks are W250mm, D160mm, H60mm (glazed) at the outer wall, and W225mm, D110mm, H60mm (unglazed) at the inner wall (Fig.2-1-2)

The roof truss of the top storey is timber structure, and the roof beams are installed by hollowing out the brick walls.



The Plan of the first storey



Section

Fig.2-1-1 Jagannath Temple (Quoted from Niels Gutschow, *ARCHITECTURE OF THE NEWARS: A History of Building Typologies and Details in Nepal, Volume II The Malla Period*, Serindia Publications, Chicago, 2011, p.417 and retouched by the editor.)

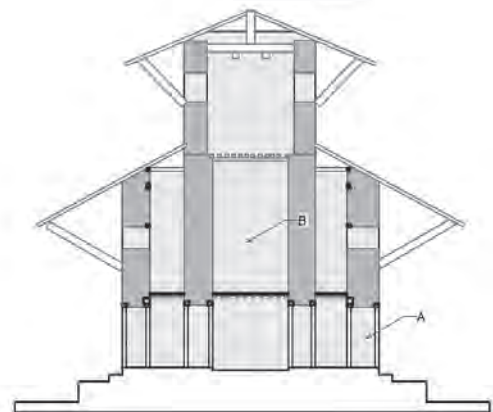
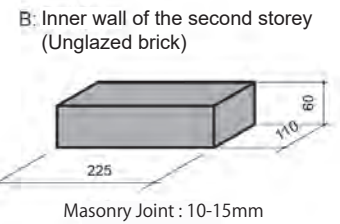
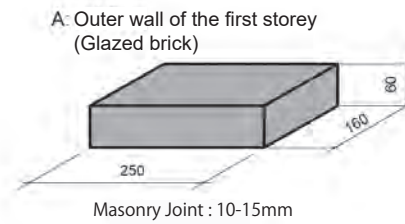
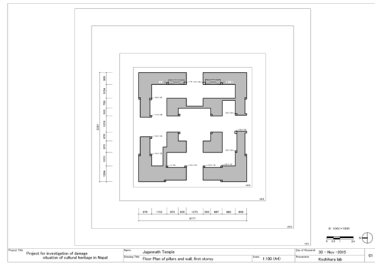
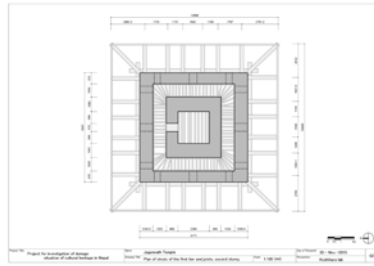


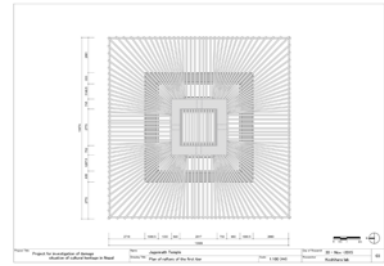
Fig.2-1-2 Brick size and the location in Jagannath Temple (Detail of bricks)



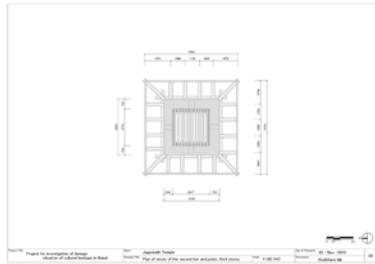
01-Floor plan of pillars and wall, 1st storey



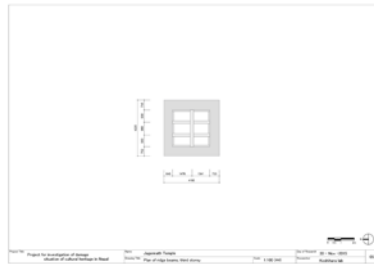
02-Plan of struts of the 1st tier and joists, 2nd storey



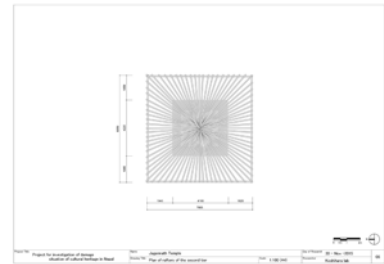
03-Plan of rafters of the 1st tier



04-Plan of struts of the 2nd tier and joists, 3rd storey



05-Plan of ridge beams, 3rd storey



06-Plan of rafters of the 2nd tier



07-North elevation



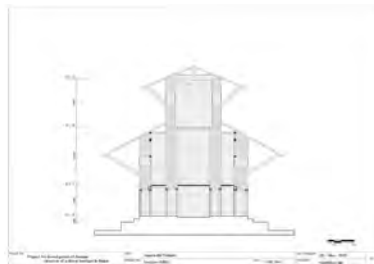
08-East elevation



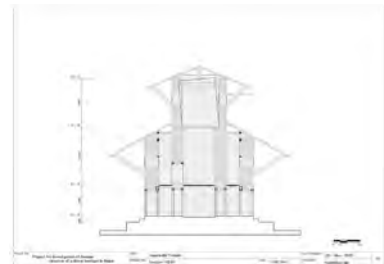
09-West elevation



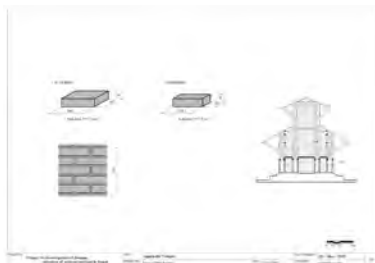
10-South elevation



11-Section of X (NS) direction



12-Section of Y (EW) direction



13-Size of bricks

Fig.2-1-3 The list of the structural drawings of Jagannath Temple

<Reference materials>

Niels gutschow, *ARCHITECTURE OF THE NEWARS :A History of Building Typologoes and Details in Nepal, Volume II The Malla Period*, Serindia Publications, Chicago, 2011

(Quoted from p.414)

History

The inscription on the pedestal of the Caturvyuha ("four kinds of appearances") Visnu in the sanctum testifies to the consecration of the image by Mahendramalla in January 1563. The stele, placed in a large jalahari with its spout facing north, features Vasudeva with club and disk (east, epithet of Krsna as the son of Vasudeva), Sankarsana with plough (south, also understood as an epithet of Balarama, the elder brother of Krsna) Pradyumna with bow and arrow (west, son of Krsna), and Aniruddha with shield and sword (north, Pradyumna's son).

Very probably, the consecration of the four-fold deity marked the completion of the construction, which must have been started by King Mahendramalla in 1561 a few months after ascending the throne. A similar temple with a Caturvyuha Visnu stele was consecrated in 1565 by King Purandarasimha in Patan, albeit based on a slightly smaller plan.

It is unknown when the identification of the temple with the "four kinds of appearances" of Visnu received a new layer dominated by Jagannatha, the Lord of the Universe from Puri, the sacred place that punctuates one of the four corners of India, the Cardham. King Sidhinarasimhamalla from Patan, who had relinquished the throne in 1652 to undertake a pilgrimage to Kasi (Benares) was probably the first to undertake a pilgrimage to Puri in the 1660s, followed by King Jagatprakasamalla from Bhaktapur in 1670. A painting preserved in the Victoria and Albert Museum in London documents this visit, stating that the Anandavrata observance was completed during the month of Bhadra (August/September).

The early temples of Puri were dedicated to Vasudeva, which among the Caturvyuha of Visnu faced east. Not before the 14th century, Vasudeva was replaced by Hinduised tribal gods, the Wooden Triad of Jagannatha, Krsna or Visnu as the Lord of the World, in the company of his sister Subhadra and his elder brother Balabhadra. Jagannatha became the uncontested imperial god (rastradevata) of the Ganga dynasty of Orissa. With the collapse of the empire, the "Little Kings" of Orissa started to establish Jagannatha temples from the early 17th century onwards in close neighbourhood to their palaces. An early identification of the Caturvyuha temple in Kathmandu with Jagannatha can be seen mirroring this trend, which was encouraged by the Pax Britannica after 1803. The early identification with Jagannatha might have been substantiated by the donation of the four aspects of Visnu worked in gilt copper repousse which cover the four sides of the stele in the month of Asadha (July), recalling Jagannatha's annual ritual journey to Gundica.

The Wooden Triad must have arrived from Orissa some time in the late 18th or even early 19th century to be somewhat provisionally placed into the eastern doorway of the inner quadrangle of the temple.

The structure

Among the seven early two-tiered temples with an inner ambulatory which date to the 13th to 16th century, this is only one in Kathmandu to rank among the smallest. Its only rival is in Patan, the Carnarayana, which is considerably smaller. The quadrangle, the length of which measures 830 centimetres, is raised on an almost two metres high, triple-stepped plinth. The second step extends diagonally to accommodate four pavilion-like two-tiered temples facing the east-west axis – a pancayana configuration that added Mahadeva, Ganasa, Surya and Durga to the central representation of Visnu.

The portals with their triple openings have survived almost completely in their original form, which date to 1563, and are flanked by aedicules. The rympana do not necessarily match the original structure, of which in the 1934 earthquake only the northern quarter of the upper roof collapsed.

With the placement of the Wooden Triad in the doorway of the inner quadrangle, two walls must have been added to block the inner ambulatory. Since that time the deities are exclusively (but at present rarely) accessible from the east, while the central stele featuring the Caturvyuha Visnu is accessible from the south. Early 19th-century photographs also reveal the blocking of the secondary doorways of the portals by walls, probably to improve the stability of the structure. The lower roof is supported by the “24 forms of Visnu” (caturvimsatimurti): with four heads and up to eight arms, the four chief attributes of the deity can be arranged in 24 different ways, each of them being regarded as a particular aspect of Visnu.

Two years after the 1934 earthquake the roofs were renewed, the veneer bricks of the ground floor were relaid up to a height of one metre in lime and brick dust mortar, and above that in mud mortar. The inner face of the wall was replaced by standardized desiapa with the frog stamped “Sri Tin Juddha Samser.” The rafters were fixed with a separate wooden bolt and the wooden cornice above the lower roof partly replaced by one moulded in lime and brick dust mortar. In 1998 part of the roof collapsed and was hastily renewed with undersized rafters at large intervals. In 2001 the roofs were again renewed by the Kathmandu Valley Preservation Trust, with rafters measuring the historical standard of 11 x 17 centimetres in section at a spacing of 17 centimetres. Structural details were not changed, but the cornice replaced in wood and paint removed from all woodwork. The plinth was restored to its original extent, newly paved, and the steps lined in stone.

2.2. Gopinath Temple

The building description of Gopinath Temple and proposed repairs by 「John Sanday, *KATHMANUDU VALLEY: Nepalese historic monuments in need of preservation*, Unesco, 1982」 are followings.

Gopinath: B/K-175
(Three-tiered temple)

Location: Hanuman Dhoka

Constructed: Seventeenth century

Deity: Gopinath

Religion: Vaishnava

Building description

This temple, standing upon a raised brick base, is adjacent to the Jagannath temple. It is of traditional design and has three tiers of roof crowned with a gajur. The sanctum is surrounded by a carved wooden colonnade and carved wooden colonnade and carved wooden struts support the lower roofs. Although its date is uncertain, it was probably built in the seventeenth century. Its principal festival usually occurs in Krishnashtami.

Proposed repairs

As part of the Jagannath group this temple is an important element in the environment. It appears generally to be in reasonable condition but requires maintenance and cleaning. It is advisable for the roof covering to be relaid and treated; the brick base will also require some attention.

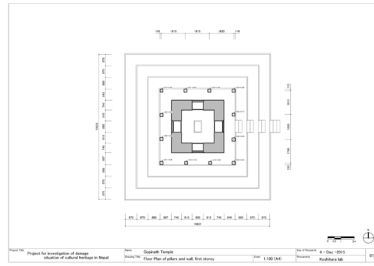
For the Gopinath Temple, as in the Jagannath Temple, structural drawings that included each framing plan of each storey and elevation, X and Y cross sections, brick detail, and more were created from the detail survey. The basic dimensions of the building and section were also recorded. Table 2-2-1 shows the list of drawings of Gopinath Temple

Tab.2-2-1 The list of the structural drawings of Gopinath Temple

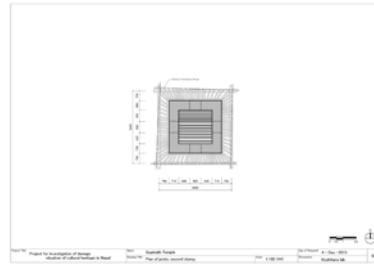
Number	Drawing Title	Scale	Note
1	Floor plan of pillars and wall, 1st storey	1 : 100	
2	Plan of joists, 2nd storey	1 : 100	Position of girder in 1st storey
3	Plan of struts and fascia boards of the 1st tier	1 : 100	Position of knee brace in 2nd storey
4	Plan of rafters of the 1st tier	1 : 100	Position of rafter in 2nd storey
5	Plan of struts of 2nd tier and joists, 3rd storey	1 : 100	Position of knee brace in 3rd storey
6	Plan of struts and fascia boards of the 3rd tier	1 : 100	Position of girder in 3rd storey
7	Plan of beams between 3rd and 4th storey	1 : 100	Position of rafter in 3rd storey
8	Plan of rafters of the 2nd tier	1 : 100	Position of knee brace in 4th storey
9	Plan of ridge beams, 4th storey	1 : 100	Position of girder in 4th storey
10	Plan of rafters of the 3rd tier	1 : 100	Position of rafter in 4th storey
11	North elevation	1 : 100	Keeping the horizontal of 3D scan data
12	East elevation	1 : 100	Keeping the horizontal of 3D scan data
13	West elevation	1 : 100	Keeping the horizontal of 3D scan data
14	South elevation	1 : 100	Keeping the horizontal of 3D scan data
15	Section of X (EW) direction	1 : 100	Drawing podium as horizontal
16	Section of Y (NS) direction	1 : 100	Drawing podium as horizontal
17	Size of bricks	1:10	



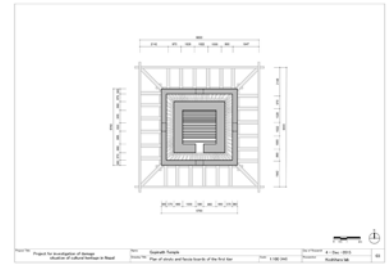
Pic.2-2-1 Timber column of the first storey which can be seen from inside of the inner wall Bricks



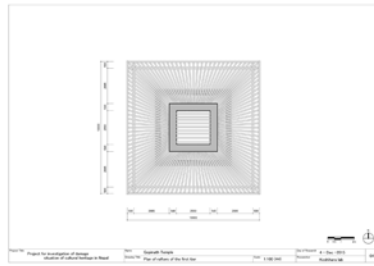
01-Floor plan of pillars and wall, 1st storey



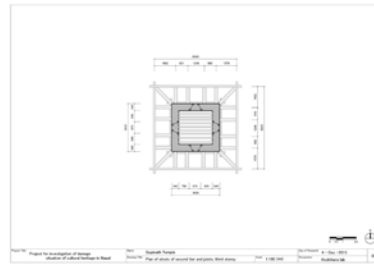
02-Plan of joists, 2nd storey



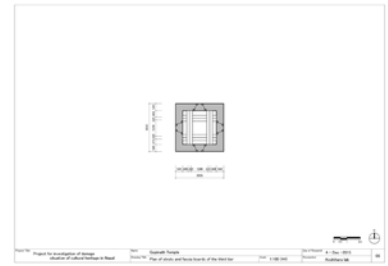
03-Plan of struts and fascia boards of the 1st tier



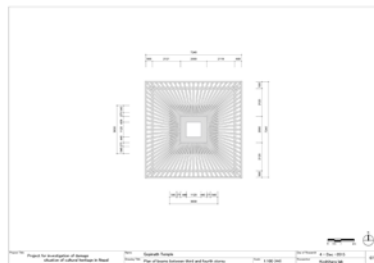
04-Plan of rafters of the 1st tier



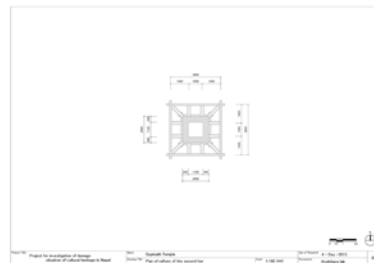
005-Plan of struts of 2nd tier and joists, 3rd storey



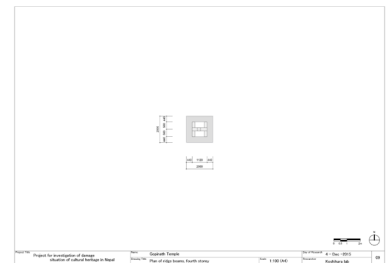
06-Plan of struts and fascia boards of the 3rd tier



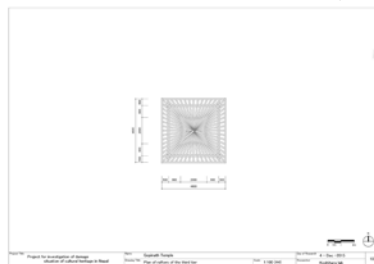
07-Plan of beams between 3rd and 4th storey



08-Plan of rafters of the 2nd tier



09-Plan of ridge beams, 4th storey



10-Plan of rafters of the 3rd tier



11-North elevation



12-East elevation



13-West elevation



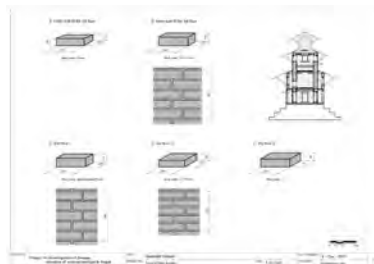
14-South elevation



15-Section of X (EW) direction



16-Section of Y (NS) direction



17-Size of bricks

Fig.2-2-1 The list of the structural drawings of Gopinath Temple

<Structure>

Plan of the first storey and the section of Gopinath Temple are shown in Fig. 2-2-2.

There are brickwork walls at the outer and inner walls of the first storey. The dimension of brick is W210mm, D115mm, H55mm (glazed, cuneiformed) at the outer wall, and W225mm, D110mm, H60mm (unglazed) at the inner wall(Fig.2-2-3). The roof truss of the top storey is timber structure, and the roof beams are crossed hollowing out the brick walls.

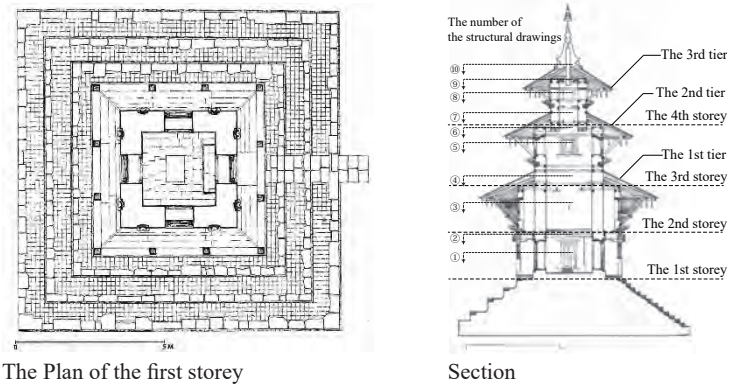


Fig.2-2-2 Gopinath Temple(Quoted from Niels Gutschow, *ARCHITECTURE OF THE NEWARS: A History of Building Typologies and Details in Nepal, Volume II The Malla Period*, Serindia Publications, Chicago, 2011, pp.481-482 and retouched by the editor.)

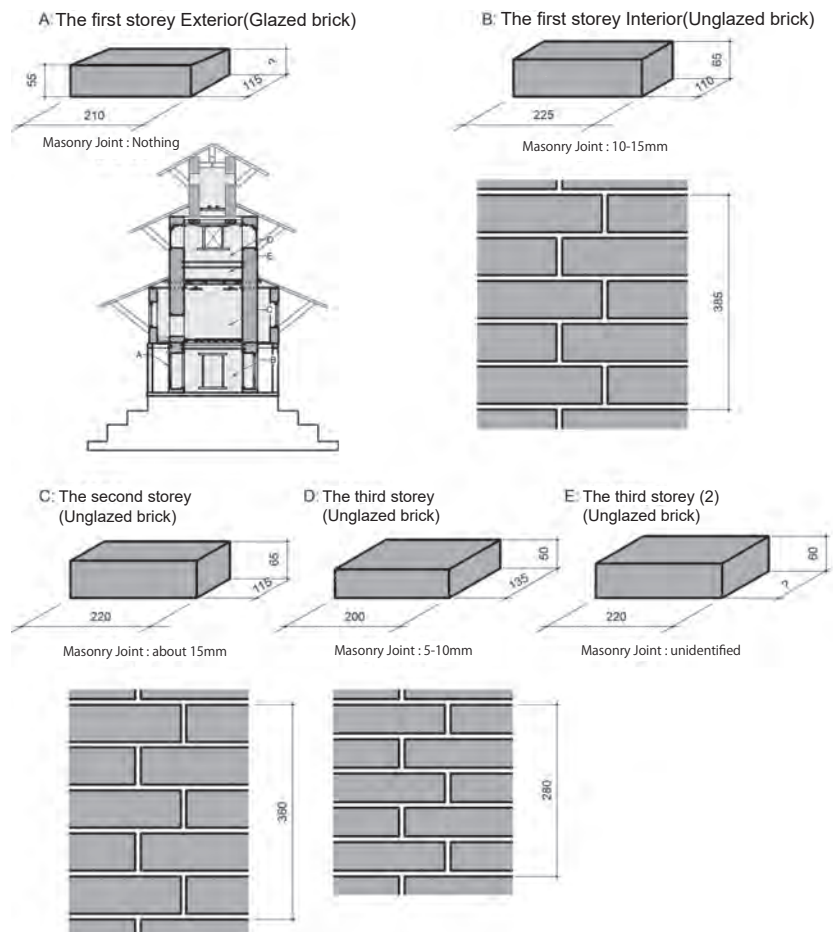


Fig.2-2-3 Brick size and location in Gopinath Temple (Detail of bricks)

<Reference materials>

Niels Gutschow, *ARCHITECTURE OF THE NEWARS: A History of Building Typologies and Details in Nepal, Volume II The Malla Period*, Serindia Publications, Chicago, 2011

(Quoted from p.481)

History

Established at the end of the 17th or even early 18th century, this triple-tiered temple with an ambulatory with twelve pillars represents the most common temple type which evolved from the early 17th century on.

The original Visnu idol has survived; the daily puja is performed by Misra Brahmins from the neighbouring quarter of Maru.

The temple collapsed in the 1934 earthquake and was subsequently re-erected in a much amended shape by the overseer and restored to its original shape by the Kathmandu Valley Preservation Trust.

The Structure

The square sanctum on the stepped plinth is accessible from the east across eleven steps, decorative doors on the other side as well as eight aedicules, columns niches with representations of the guardians of the directions, thus avoiding a hierarchy among the four sides. Most striking is the introduction of struts with an interval of blank surface between the presentation of two-handed deities and caryatid-like supporting apsaras. Across this plain surface spans a decorative bar with kulan pattern, suggesting the existence of latticework.

After the 1934 earthquake, the ground floor wall was plastered, and the surface of it painted with a brick pattern. Twenty-two of the old struts were re-used but shortened to rest on a projecting course of bricks – a configuration which distorted the proportions of the temple considerably. For the surface of the upper walls maapa were used; the struts supporting the uppermost roof were reused from a collapsed temple.

In 2003 the Kathmandu Valley Preservation Trust dismantled all the roofs and the brickwork above the cornice on the top of the lower roof. The pillars, beam and cornice on top were kept in situ, and the plinths and the wall of the sanctum refaced with veneer bricks (datiapa), leaving the doors in their fragmented shape without the outer puratva, frame and without the usual widened inner frame. Based on the evidence of the blank intermediate surface and of 19th century photographs, the original configuration with latticework and dividing bar was restored. To achieve that, the struts had to be lengthened.

2.3. Building material and construction method

2.3.1. Building material

The main materials of buildings are brick and timber.

(1) Brick

Burned brick is used. According to 「Purusottam Dangol, *Elements on Nepalese Temple Architecture*, Adroit Publishers, 2007」, major types of bricks are as below.

Māapā Traditional brick with one end and one edge glazed.

Bāapā Moulded and decorated brick

Kūapā Corner brick

Dachīapā It is both wedged and glazed.

Measurement results of weight, size, and shape of new bricks for repair which is equivalent to *Dachīapā* are shown in Table 2-3-1.



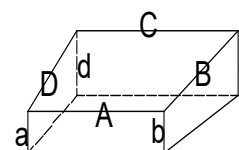
Pic.2-3-1 Bricks for repairing



Pic.2-3-2 Appearance of measurement of weight, size and shape of th bricks

Tab.2-3-1 Weight, size and shape of bricks

	Weight(kgf)	Size(mm)								Area mm ²	(a+b+c+d)/4 mm	Volume cm ³	Density g/cm ³
		A	B	C	D	a	b	c	d				
Trapezium 1	2.33	190	130	214	130	47	45	60	58	26148	52.5	1373	1.70
Trapezium 2	2.078	184	123	204	125	43	46	58	58	23857	51.3	1223	1.70
Trapezium 3	2.104	188	122	205	122	46	48	58	58	23915	52.5	1256	1.68
Trapezium 4	2.008	185	124	205	125	45	44	57	56	24169	50.5	1221	1.65
Trapezium 5	2.334	194	130	212	127	48	50	59	58	25657	53.8	1379	1.69
Trapezium 6	2.008	188	125	203	123	45	42	55	56	23982	49.5	1187	1.69
Trapezium 7	2.286	190	128	210	130	47	46	55	56	25593	51.0	1305	1.75
Trapezium 8	2.062	180	124	205	123	43	40	56	57	23633	49.0	1158	1.78
Trapezium 9	2.082	180	120	200	126	42	40	55	57	22220	48.5	1078	1.93
Trapezium 10	2.224	191	126	208	125	45	45	57	57	24937	51.0	1272	1.75
Trapezium Aver	2.152	187	125.2	206.6	125.6	45.1	44.6	57	57.1	24411	51.0	1245	1.73





Appearance of brick for repairing



ABCD side



C side



D side



A side



B side

Pic.2-3-3 The shape of bricks for repairing the damaged temples near Jaganannth Temple

(2) Timber

Main tree species are Agrak (Sal) for the structural frame, and Salla (Pine) for the hidden members.

(3) Material characteristics

Material characteristics which are presumed by former surveys and analyses are shown in Table2-3-2.

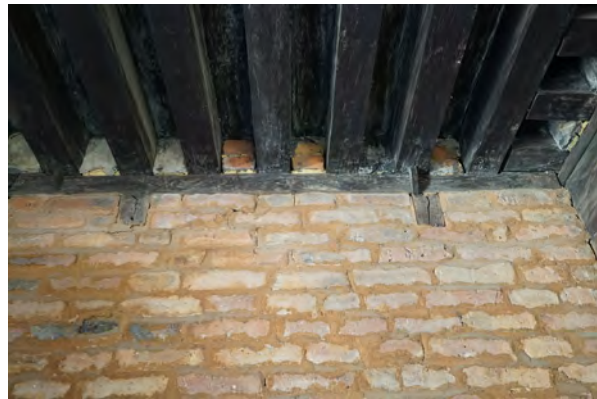
Tab.2-3-2 Material characteristics (Quoted from Disaster Risk Management for the Historic City of Patan, Nepal, R-DMUCH, March 2012, p.98)

Variable	Burned Brick	Mortar	Wood
Mass density	1.8×10^3	-	7.0×10^2
Young's Modulus(N/m^2)	2.7×10^8	2.7×10^8	6.3×10^8
Poisson's ratio	0.11	0.25	0.3
Tensile strength(N/m^2)	-	0	1.1×10^8
Shear strength(N/m^2)	-	9.0×10^4	9.0×10^6
Friction angle ϕ	-	42.5°	0°
Compressive strength (N/m^2)	-	1.58×10^6	4.5×10^7

2.3.2. Construction method

The Floor and roof (Horizontal plane):

The floor and roof which have function as horizontal plane are constructed with timber. Timber member which is orthogonal to the member on the top of the wall is fixed with timber wedge from both sides.



Pic.2-3-4 Joint corner between walls and floor (Timber element which is orthogonal to the element on the top of the wall is fixed with the timber wedge from both sides.)



3. Earthquake Damage

3. Earthquake Damage

3.1. Structure of the multi-tiered tower

The main structure of multi-tiered tower in the Jagannath and Gopinath Temples were constructed using brick walls and timber frames. Considering a building's structure to resist its own weight, those could be classified into the following three types: (A) buildings primarily constructed with brick walls, (B) buildings primarily constructed with timber frames, and (C) buildings whose timber frames are built inside brick walls. Among these classifications, Building type C suffer fewer total building collapses because the timber frames resist their own weight despite collapse and loss of structural function of the brick walls, as shown in Pic. 3-1-1. The mixed structural system characteristics of multi-tiered tower of Newar architecture likely contribute to their superior seismic performance.



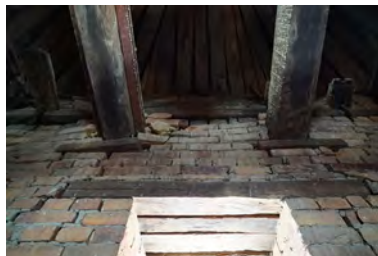
Pic.3-1-1 Changu Narayan Temple structure saved from collapse by the timber columns inside of the brick wall

3.2. Damage of Jagannath Temple

As shown in Pic. 3-2-1 damage to the Jagannath Temple following the Gorkha Earthquake was concentrated in the third (top) storey of the building. The shear failure of the brick walls appeared at the cut-out for the roof beam. The shear failure was concentrated in the joint between bricks; failure of the brick itself was not observed.



Third (top) storey: Brick wall damage



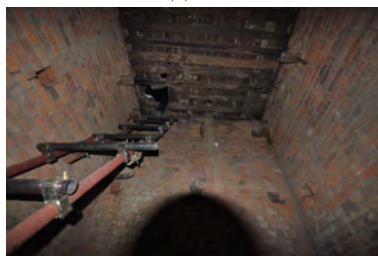
Third (top) storey: Crack from the cut-out for the beam (1)



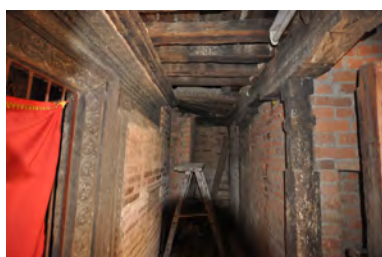
Third (top) storey: Crack from the cut-out for the beam (2)



Second storey: Slight damage to inside and outside wall



Second storey: Slight damage to inside wall



First storey: Slight damage



First storey: Slight damage



Annex towers: Heavy damage

Pic.3-2-1 Earthquake damage to Jagannath Temple

Jagannath Temple was collapsed by Nepal-Bihar earthquake in 1934 and rebuilt.



Pic.3-2-2 The Hanuman Dhoka Palace after 1934 Nepal-Bihar earthquake (the temple at rear-right side is Jagannath Temple)

*Nepal-Bihar earthquake

“The 1934 Nepal-Bihar earthquake was one of the worst earthquakes in the history of Nepal and Bihar, India. This 8.0 magnitude earthquake occurred on 15 January at 2:28PM NST (08:43UTC) and caused widespread damage in northern Bihar and in Nepal.

The epicentre for this event was located in eastern Nepal about 9.5 km (5.9 mi) south of Mount Everest. The areas where the most damage to life and property occurred extended from Purnea in the east to Champaran in the west (a distance of nearly 320 km (200 mi)), and from Kathmandu in the north to Munger in the south (a distance of nearly 465 km (289 mi)). The impact was reported to be felt in Lhasa to Bombay, and from Assam to Punjab. The earthquake was so severe that in Kolkata, around 650 km (404 mi) from epicenter, many buildings were damaged and the tower of St. Paul's Cathedral collapsed” (Quoted from Wikipedia, https://en.wikipedia.org/wiki/1934_Nepal%E2%80%93Bihar_earthquake, accessed 15 August 2016)

Source: Brahma Shumsher Jung Bahadur Rana, Ratna Pustak Bhandar, *The Great Earthquake in Nepal 1934 A.D.*, Kathmandu, Nepal, 2013

3.3. Damage of Gopinath Temple

As shown in Fig. 3-3-1, the Gopinath Temple was supported with a temporary column and knee brace as an emergency measure against the earthquake damage. The knee brace provided additional support at the east and south sides of the structure; residual deformation to the east or southeast direction was likely. As shown in Pic. 3-3-1, structural damage to the Gopinath Temple was concentrated in the first storey. Primary structural damage included collapsed brick wall joints, peeled inner wall plaster, and fallen timber beams at the periphery. Conversely, wall damage in the second and third storey was not observed.

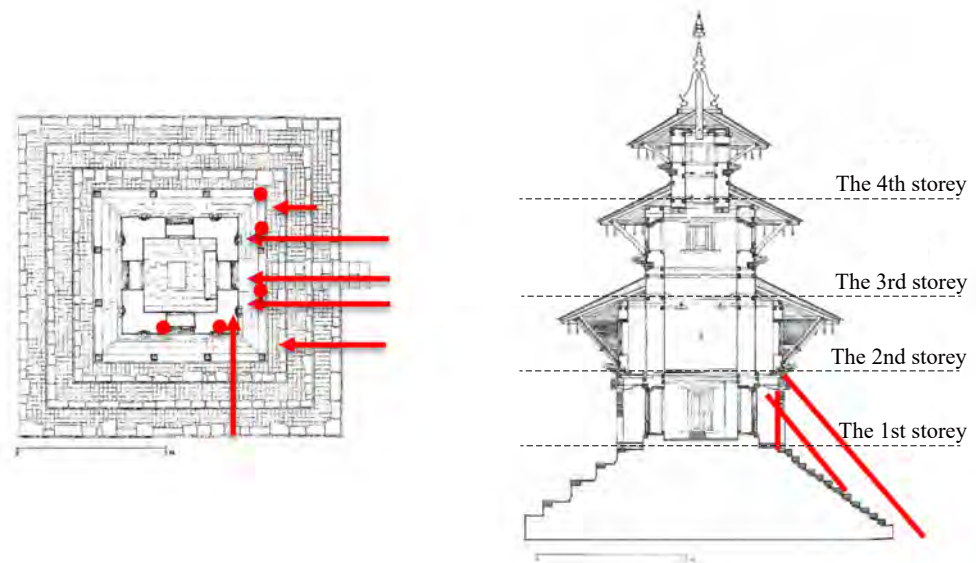
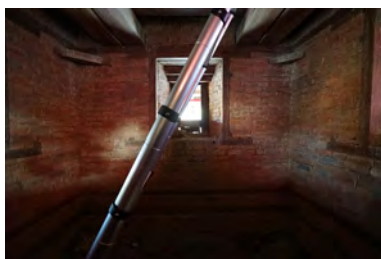
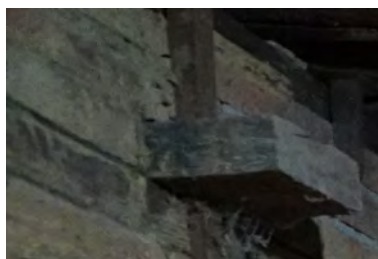


Fig3-3-1 The supports as an emergency measure implemented to Gopinath Temple



Third storey: Slight outer wall damage



Second storey: Slight inner wall damage



First storey: Peeling plaster from inner wall and damage at the masonry joint

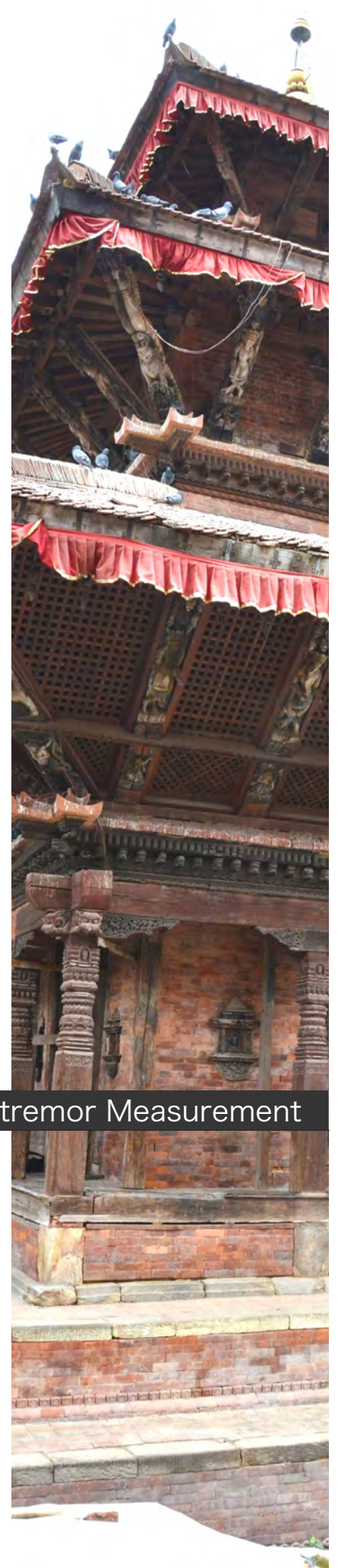


First storey: Damage at the masonry joint at outer wall



Timber beam coming out from the column

Pic.3-3-1 Earthquake damage to Gopinath Temple



4. Micro-tremor Measurement

4. Micro-tremor Measurement

Micro-tremors were measured to identify the natural frequency and vibration mode of each subject building. Multiple measurements were taken: one on free ground, one on the stepped plinth, and several inside the buildings. The measurement point on free ground was at the front of the building. The measurement point on the stepped plinth was intended to detect any vibration amplification by the stepped plinth structure. Measurement points inside the buildings were at the top of the wall, on the beam, and on each storey close to a structural wall. The measurements were obtained using a portable vibration monitoring system (SPC-51) and servo-velocity meters (VSE-15D) produced by Tokyo-Sokushin.



Pic.4-0-1 Portable vibration monitoring system (SPC-51)



Pic.4-0-2 Servo-velocity meters (VSE-15D)

4.1. Jagannath Temple

Micro-tremor measurements were performed on Jagannath Temple, as shown in Pic.4-1-1, from 2 to 3 December, 2015. Two horizontal components of vibration were measured at the center of the walls of each storey.

Measurement case, starting time (in Japan Standard Time), and measuring direction are shown in Table 4-1-1. 16 cases of measurements were performed.



(a) External appearance



(b) Outer corridor at the first storey



(c) Outer corridor at the second storey



(d) The third storey

Pic.4-1-1 Jagannath Temple

Tab.4-1-1 Measurement cases, start time and measuring direction

Case	Start time (in JST)	Direction
1	2nd December, 2015, 21:42:51:00	EW
2	2nd December, 2015, 22:07:03:10	NS
3	2nd December, 2015, 22:22:43:06	NS
4	2nd December, 2015, 22:37:49:00	EW
5	2nd December, 2015, 23:05:22:46	EW
6	3rd December, 2015, 00:12:48:46	EW
7	3rd December, 2015, 00:33:04:00	NS
8	3rd December, 2015, 00:48:29:17	NS
9	3rd December, 2015, 01:14:43:00	NS
10	3rd December, 2015, 01:27:44:00	NS
11	3rd December, 2015, 01:51:57:35	EW
12	3rd December, 2015, 02:02:22:00	EW
13	3rd December, 2015, 02:29:40:39	EW
14	3rd December, 2015, 02:41:10:15	EW
15	3rd December, 2015, 03:05:21:32	NS
16	3rd December, 2015, 03:18:02:13	NS

All measurement points are shown in Fig.4-1-1. All measurement points were monitored by dividing into 16 cases shown above. Multiple measurements were taken: one on free ground, and several inside the buildings. The measurement point on free ground was at the front of the building, shown in Pic.4-1-2(a). The measurement point on the stepped plinth was also intended to confirm the amplification of the vibration by the stepped plinth. Measurement points inside the building were at the top of the wall, on the beam, and on each floor close to a structural wall. Since it was difficult to put the sensor on the top of the wall at the top storey, we placed it on the beam beside the wall as shown in Pic.4-1-2(b).

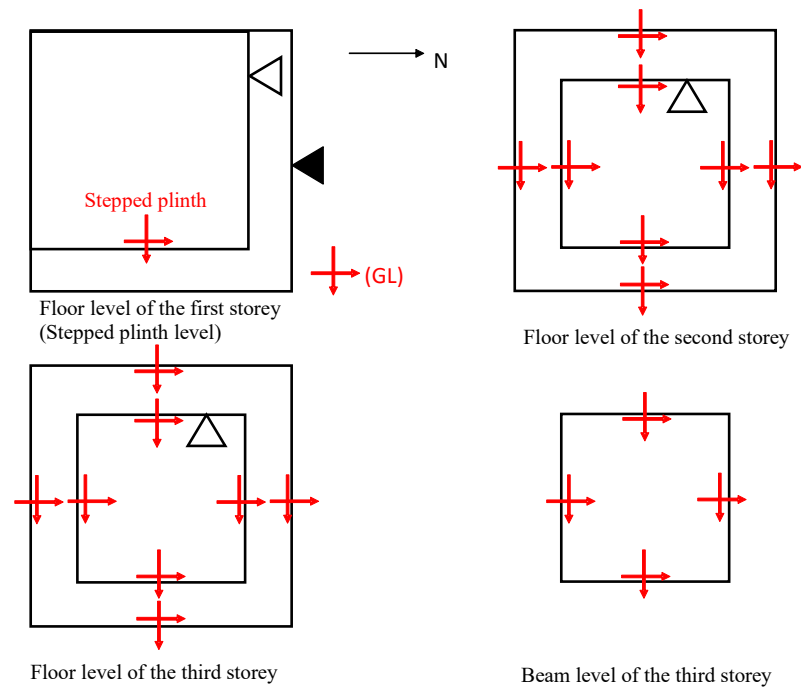


Fig.4-1-1 All measurement points on Jagannath Temple



(a) On the free ground



(b) On the beam of the third storey

Pic.4-1-2 Measurement points

As a representative measurement result for Jagannath Temple, the result of first measurement in the east-west (EW) direction are shown below.

The measurement was performed by placing 5 sensors (Ch1-Ch5) as shown in Fig. 4-1-2. The transfer function was obtained by dividing the Fourier spectrum of building vibration monitored inside the building by the Fourier spectrum of ground vibration. The peak frequencies of the transfer function—2.6 Hz, 4.5 Hz, and 8.5 Hz—were estimated to be first, second, and third natural frequencies of the building (Fig. 4-1-3). The vibration mode of elevation corresponding to the first, second, and third natural frequencies in E-W direction are shown in Fig. 4-1-4. At the first vibration mode, the amplitude of the third storey is larger than that of the first and second storey. At the second and third vibration modes, each wall line has different vibration direction, thus it is presumed that the rigidity of the horizontal plane is not sufficient.

Pic.4-1-3 shows the placed sensors. Ch3 was placed on the floor beside wall, and Ch5 was placed on the beam beside wall in the measurement. Besides, Ch5 was fixed at same place for calibration in order to compare the vibration amplitude.

Fig.4-1-5 to Fig.4-1-10 similarly show the first, second and third vibration modes obtained by other measurement cases. The plan of each storey and section of each direction are drawn to simplify the figure.

Moreover, the detail data and the results by other measurement cases are shown in Appendix A.1 to A.16.

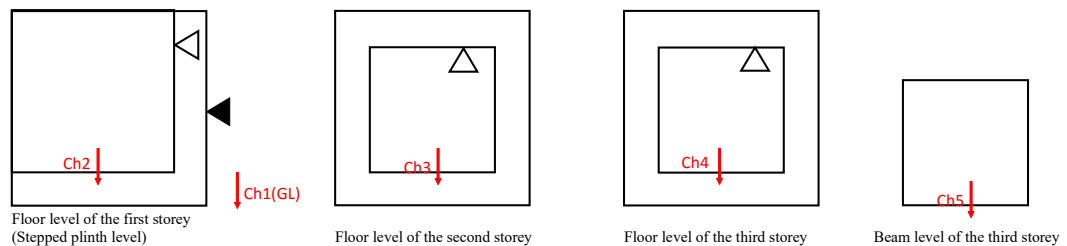


Fig.4-1-2 Measurement arrangement (1st time of the measurement, EW direction)



(a) CH3 (on the first floor)



(b) CH5 (on the beam of the third storey)

Pic.4-1-3 Placed sensors

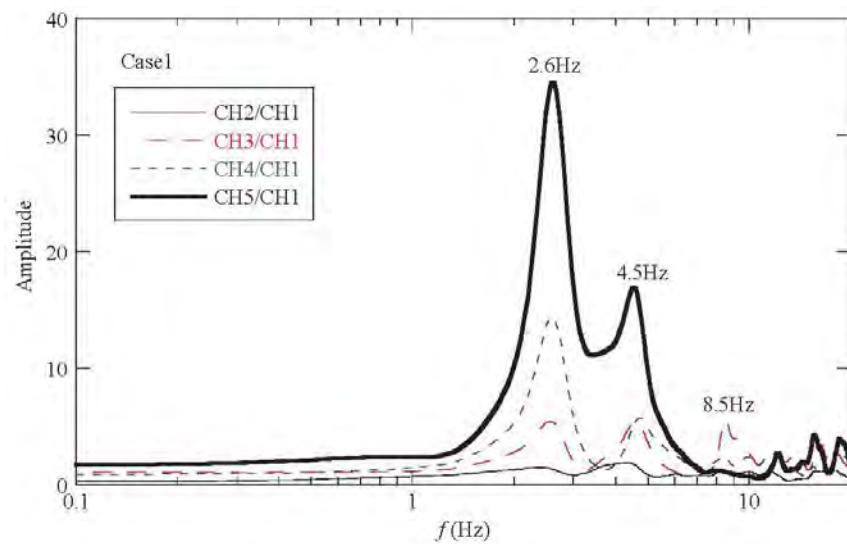
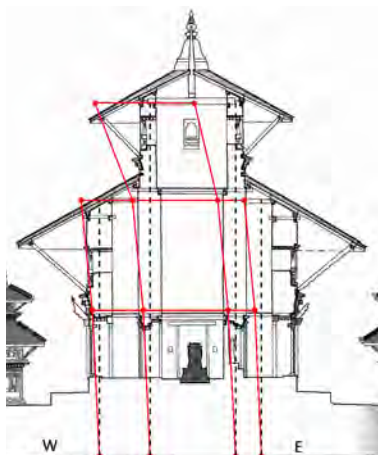
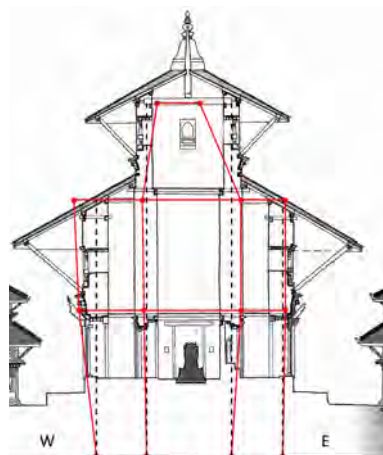


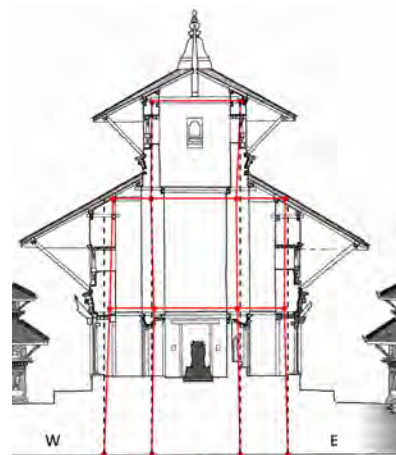
Fig.4-1-3 Representative fourier amplitude ratio for Jagannath temple (EW direction)



First vibration mode

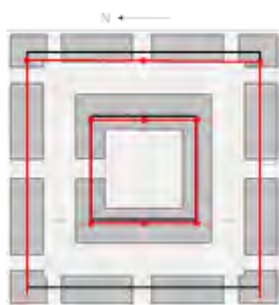


Second vibration mode

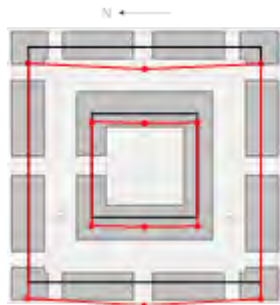


Third vibration mode

Fig.4-1-4 Representative vibration mode for Jagannath Temple (EW direction)



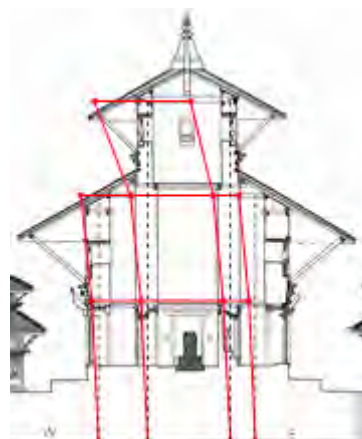
(a) 1st storey



(b) 2nd storey

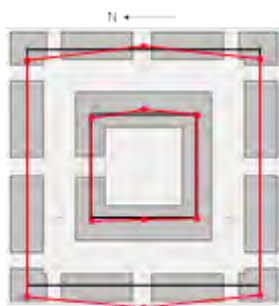


(c) 3rd storey

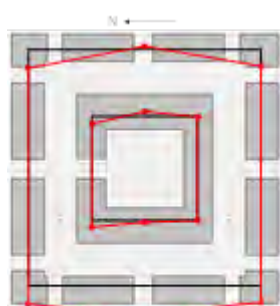


(d) Section

Fig.4-1-5 First vibration mode (EW direction)



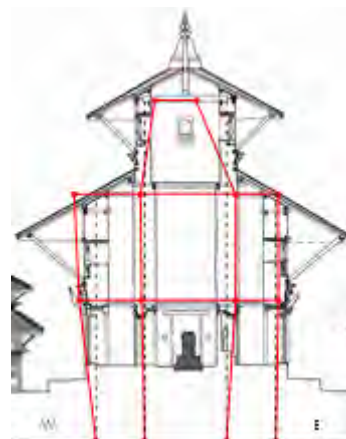
(a) 1st storey



(b) 2nd storey

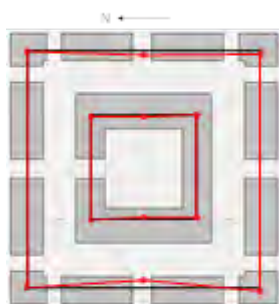


(c) 3rd storey

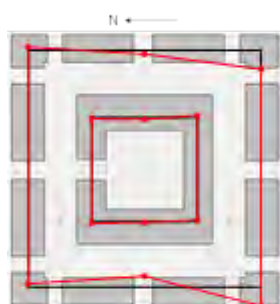


(d) Section

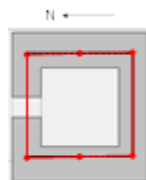
Fig.4-1-6 Second vibration mode (EW direction)



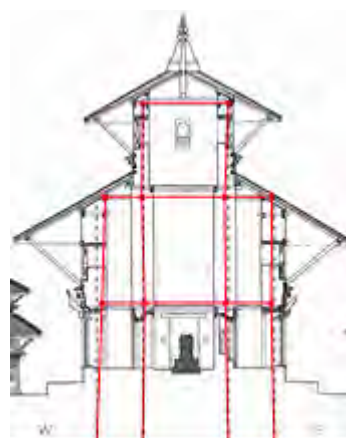
(a) 1st storey



(b) 2nd storey

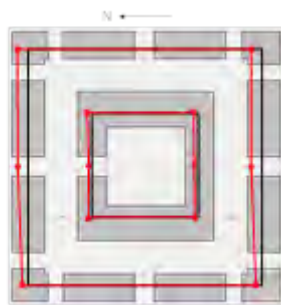


(c) 3rd storey

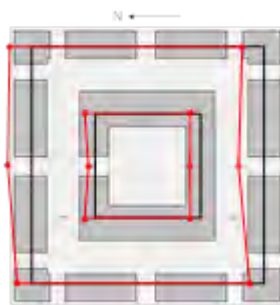


(d) Section

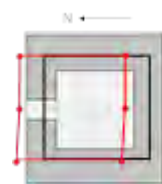
Fig.4-1-7 Third vibration mode (EW direction)



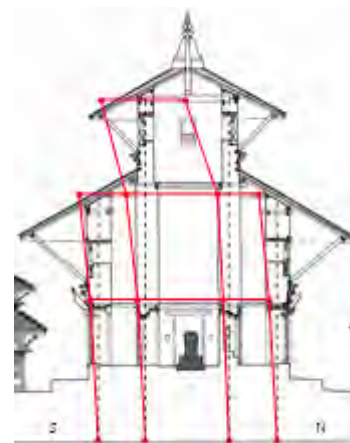
(a) 1st storey



(b) 2nd storey

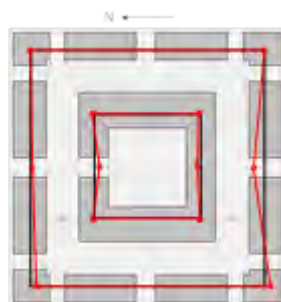


(c) 3rd storey

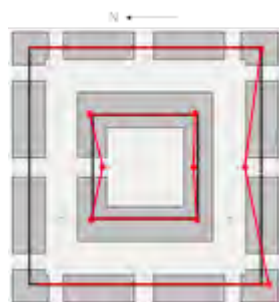


(d) Section

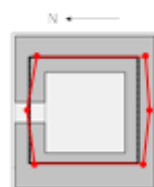
Fig.4-1-8 First vibration mode (NS direction)



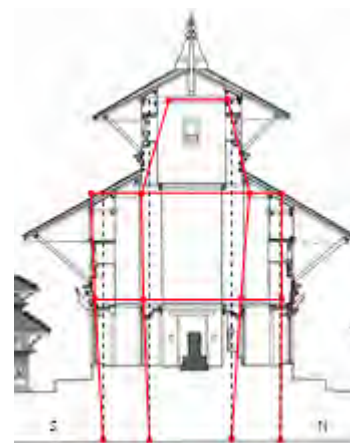
(a) 1st storey



(b) 2nd storey

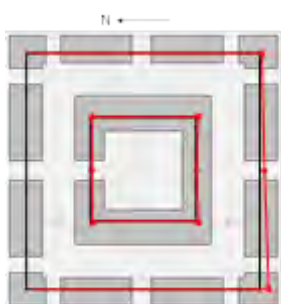


(c) 3rd storey

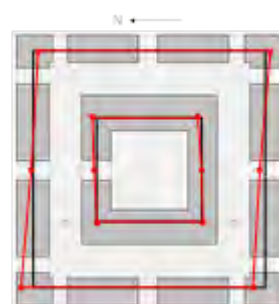


(d) Section

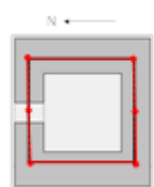
Fig.4-1-9 Second vibration mode (NS direction)



(a) 1st storey



(b) 2nd storey



(c) 3rd storey



(d) Section

Fig.4-1-10 Third vibration mode (NS direction)

4.2. Gopinath Temple

Micro-tremor measurements were performed on Gopinath Temple, as shown in Pic.4-2-1, from 4 to 5 December, 2015. Two horizontal components of vibration were measured at the top of the walls of each storey. Measurement case, starting time (in Japan Standard Time) and measuring direction are shown in Table 4-2-1. 20 cases of measurements were performed, excluding 2 unsuccessful measurements.



(a) Exterior appearance



(b) Outer corridor at the second storey



(c) Interior view of the third storey



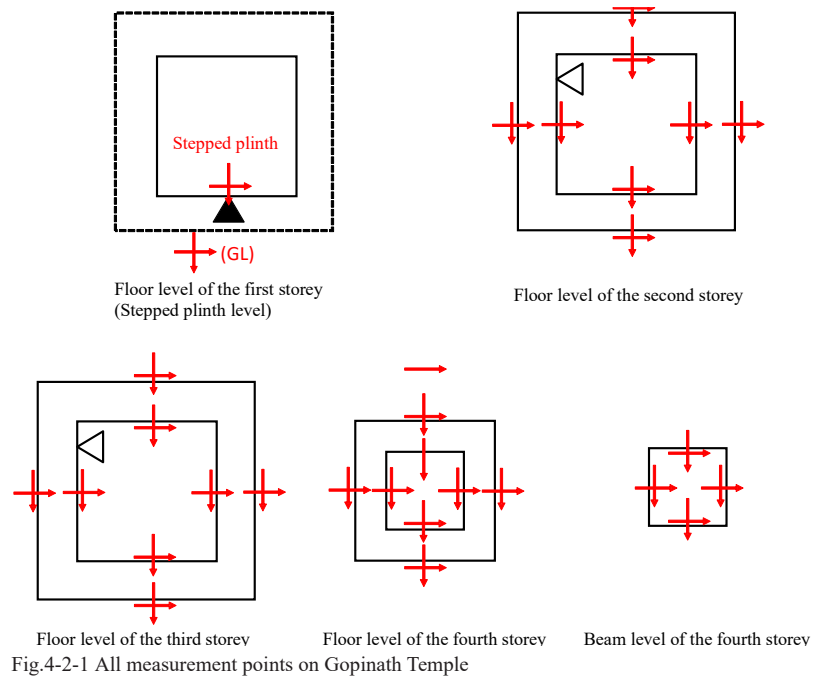
(d) The fourth storey (Photo taken from the beneath)

Pic.4-2-1 Gopinath Temple

Tab.4-2-1 Measurement cases, starting time and measuring direction

Case	Start time (in JST)	Direction	Note
1	4th December, 2015, 23:24:28:14	NS	
2	4th December, 2015, 23:41:18:06	EW	
3	5th December, 2015, 00:10:25:11	EW	
4	5th December, 2015, 00:34:14:58	NS	
5	5th December, 2015, 01:12:08:02	NS	
6	5th December, 2015, 01:32:11:02	EW	
7	5th December, 2015, 01:55:45:03	EW	
8	5th December, 2015, 02:12:25:06	NS	
9	5th December, 2015, 02:36:22:53	NS	
10	5th December, 2015, 02:59:15:54	EW	
11	5th December, 2015, 03:58:30:60	EW	
12-1	5th December, 2015, 04:18:34:08	NS	Failure
12-2	5th December, 2015, 04:33:37:05	NS	
13	5th December, 2015, 05:05:24:07	NS	
14	5th December, 2015, 05:14:56:04	EW	
15	5th December, 2015, 05:29:49:06	EW	
16	5th December, 2015, 05:49:47:12	NS	
17-1	5th December, 2015, 06:08:50:12	NS	Failure
18	5th December, 2015, 06:26:34:05	EW	
17-2	5th December, 2015, 06:36:35:04	NS	
20	5th December, 2015, 06:49:28:11	NS	
19	5th December, 2015, 06:59:04:56	EW	

All measurement points are shown in Fig.4-2-1. All measurement points were monitored by dividing into 20 cases shown above. Multiple measurements were taken: one on free ground, and several inside the buildings. The measurement point on free ground was at the front of the building, shown in Pic.4-2-2(a). The measurement point on the stepped plinth was also intended to confirm the amplification of the vibration by the stepped plinth. Measurement points inside the building were at the top of the wall, on the beam, and on each floor close to a structural wall. Since it was difficult to put the sensor on the top of the wall at the top storey, we placed it on top of the window sill in the opening as shown in Pic.4-2-2(b).



(a) On the free ground



(b) On the beam of the third storey

Pic.4-2-2 Measurement points

As a representative measurement result for Gopinath Temple, the result of first measurement in the east-west (EW) direction are shown below.

The transfer function, shown in Fig. 4-2-2, was obtained by dividing the Fourier spectrum of building vibration monitored inside the building by the Fourier spectrum of ground vibration. The peak frequencies of the transfer function—2.0 Hz, 4.5 Hz, and 7.4 Hz—were estimated to be first, second, and third natural frequencies of the building.

The vibration mode of elevation obtained by Transfer Function and phase information corresponding to the first, second and third natural frequencies in EW direction are shown in Fig.4-2-3. At the first vibration mode, the amplitude of out-of-plane direction on top of inner periphery is large. At the second and third vibration modes, the amplitude of northern structural plane is large.

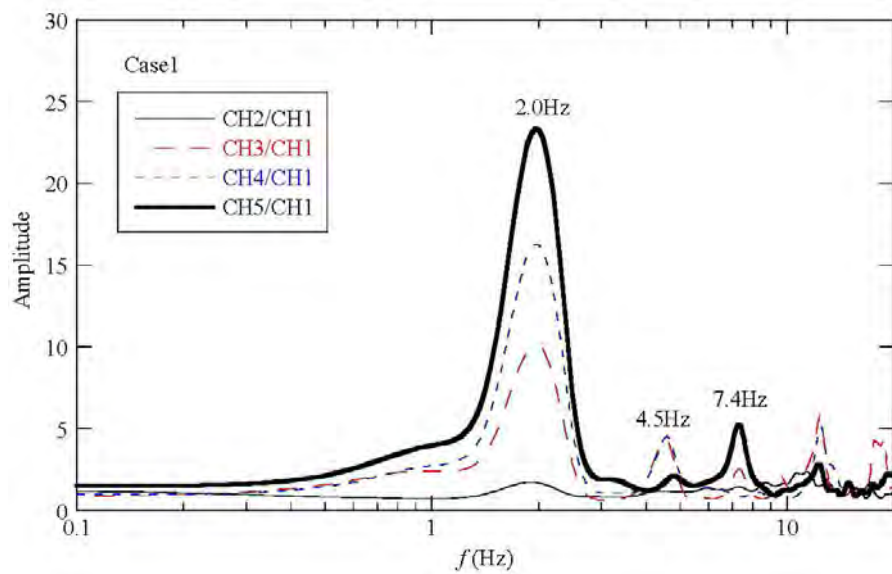
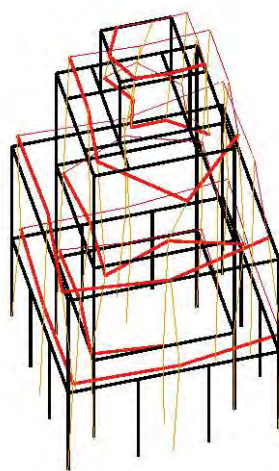
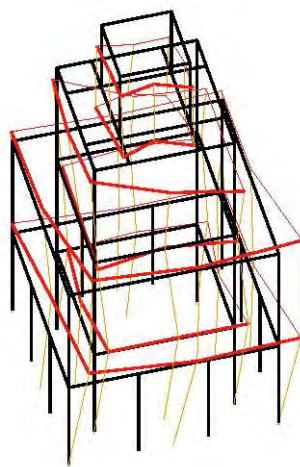


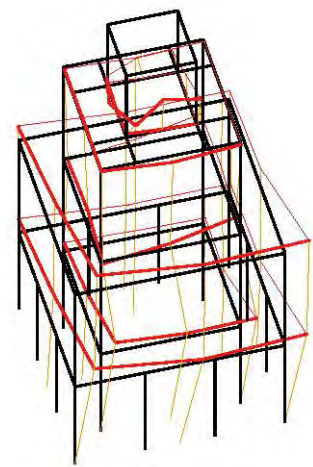
Fig.4-2-2 Representative fourier amplitude ratio for Gopinath temple (EW direction)



First vibration mode



Second vibration mode



Third vibration mode

Fig.4-2-3 Representative vibration mode for Gopinath Temple



(a) Ch4 (On the floor)



(b) Ch5 (On the top of the wall)

Pic.4-2-3 Placed sensors

Pic.4-2-3 shows the placed sensors. Ch4 was placed on the floor beside wall, and Ch5 was placed on the on top of the wall in the measurement.

Besides, Ch5 was fixed at same place for calibration in order to compare the vibration amplitude.

Fig.4-2-4 shows the vibration modes obtained by other measurements. The roof shape is removed to simplify the figure. Since the mode figure is complex and difficult to distinguish, the vibration mode of inner structural plane, outer structural plane and structural plane of the top storey were drawn dividedly.

Moreover, the detail data and the results by other measurement cases are shown in Appendix A.17 to A.36.

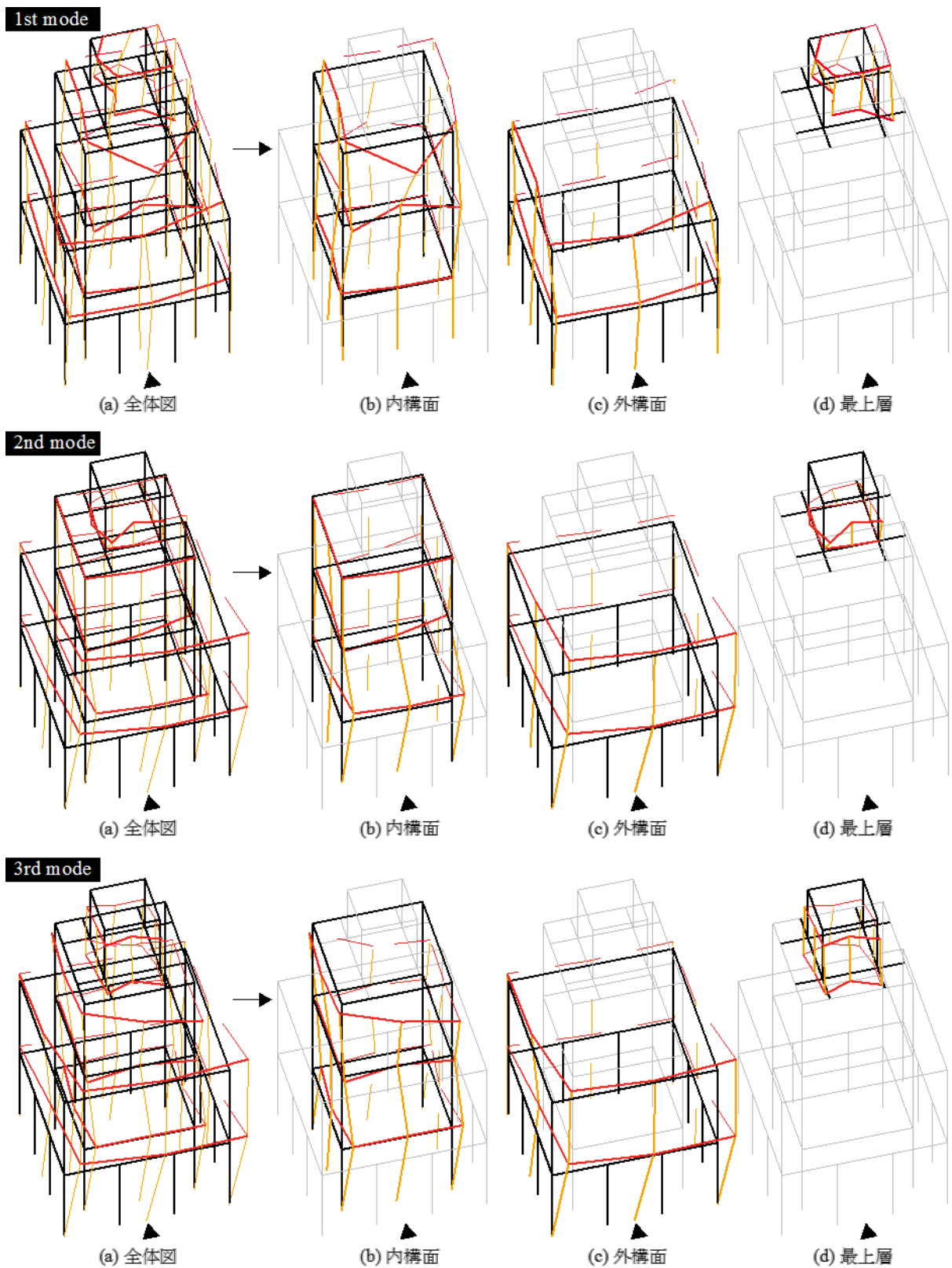
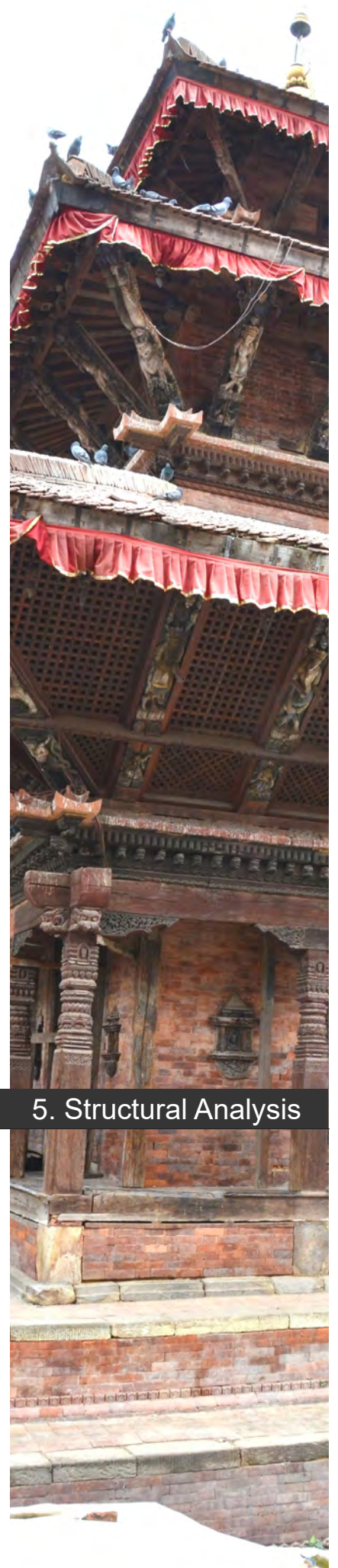


Fig.4-2-4 Vibration mode for Gopinath Temple



5. Structural Analysis

5. Structural Analysis

5.1. Seismic performance evaluation

At the occasion of evaluating the seismic performance of buildings, it is preferable to create a 3D analysis model using line, surface and joint elements as shown in Fig. 5-1-1. These models can better apply to the building conditions that may include non-true vertical planes (e.g. a wall is not straight between upper and lower storeys), insufficient rigidity in horizontal planes (e.g. floor beams and roof trusses are not sufficient), or unconfirmed rigid floor assumptions. This analysis considered performance against input earthquake vibration in conjunction with the previously developed mass point model that considers building weight and height, and previously reported performance results for brick structure (sufficient original data could not be collected within the scope of this survey). The analysis results were intended to support future reinforcement of historical buildings in Nepal.



Jagannath Temple



Gopinath Temple

Fig.5-1-1 Examples of the 3D analysis model

When evaluating seismic performance, an initial parametric study was conducted to determine appropriate constants and accepted assumptions. The parameter values and assumptions used in this evaluation were as follows:

- Shear failure of brick itself is rarely observed, brick wall failure typically appears only at the brick joints.
- The shear strength of mortar joints, F_s , was set as 0.15 N/mm^2 or $0.0867 + 0.9\sigma_c$ based on experimental results reported in 「Disaster Risk Management for the Historic City of Patan, Nepal, Ritsumeikan University Institute of Disaster Mitigation for Urban Cultural Heritage (Rits-DMUCH) 2012, p.98:Table 5-1-1」.
- If mortar joints fail, the friction force between bricks is the primary resistance. The coefficient of static friction, μ , was set as 0.5.

Tab.5-1-1 Estimated parameters for various material

Variable	Burned Brick	Mortar	Wood
Mass density	1.8×10^3	-	7.0×10^2
Young's Modulus(N/m^2)	2.7×10^8	2.7×10^8	6.3×10^8
Poisson's ratio	0.11	0.25	0.3
Tensile strength(N/m^2)	-	0	1.1×10^8
Shear strength(N/m^2)	-	9.0×10^4	9.0×10^6
Friction angle ϕ	-	42.5°	0°
Compressive strength (N/m^2)	-	1.58×10^6	4.5×10^7

5.2. Seismic performance of Jagannath Temple

Fig. 5-2-1 shows the weight of each mass point in the Jagannath Temple analysis model. Rooftop pinnacles, small openings, and wall thickness differences were ignored in the weight calculation. Table 5-2-2 lists the A_i distribution obtained from this weight calculation. Fig. 5-2-2 shows the A_i distribution when $C_b=0.1$.

Assuming that the A_i distribution is equal to the acceleration distribution, an input acceleration of 0.25 G ($C_1 = 0.25$) resulted in an output acceleration at the top storey of 0.482 G. Thus the output acceleration may exceed 0.5 G, namely the external force may be larger than the friction resistance between bricks ($\mu=0.5$) at the top storey. This assumption corresponds with the field survey results for the Jagannath Temple that noted the earthquake damage concentrated at the top storey. A similar tendency is likely observed for buildings with upper storey walls that continue straight to the first storey.

Tab.5-2-1 Estimated building weight of Jagannath Temple

Storey of mass point model	Position	Elements	a (m)	b (m)	t (m)	Unit (kN/m ²)	Modulus	Weight (kN)			Mass (tonf)
								Elements	Position	Storey	
M3	Roof of	Roof tiles Roof Truss	8.00	8.00	1.00	2.4	1.2	184			
			8.00	8.00	1.00	0.2	1	13	197		
	Wall		1.80	13.20	0.60	18	1	257	257	454	46
M2	Roof of	Roof tiles Roof Truss	13.50	13.50	1.00	2.4	1.2	525			
			4.20	4.20	-1.00	2.4	1.2	-51	474		
	Floor	Floor beams	13.50	13.50	1.00	0.2	1	36			
			4.20	4.20	-1.00	0.2	1	-4	33		
	Wall	Inner Outer	4.20	4.20	1.00	0.6	1	11	11		
			2.50	13.20	0.90	18	1	535			
			1.80	28.80	1.00	18	1	933	1468	2242	229
M1	Wall	Inner Outer	2.50	13.20	0.90	18	1	535			
			2.40	28.80	1.00	18	1	1244	1779		
	Floor	Floor beams	8.00	8.00	1.00	0.6	1	38	38		
	Wall	Inner Opening	1.25	13.20	0.90	18	1	267			
			1.00	1.10	0.90	18	-4	-71			
	Wall	Outer Opening	1.25	28.80	1.00	18	1	648			
			1.00	1.10	1.00	18	-4	-79	765	2582	263
M0	Wall	Inner Opening	1.25	13.20	0.90	18	1	267			
			1.25	1.10	0.90	18	-4	-89			
		Outer Opening	1.25	28.80	1.00	18	1	648			
			1.25	1.10	1.00	18	-4	-99	727	727	74
Total										6005	613

Tab.5-2-2 A_i distribution at each storey for Jagannath Temple

Storey of mass	w_i (kN)	$W_i=\Sigma w_i$ (kN)	α_i W_i/W	A_i	C_i			Q_i	
					0.1	0.25	0.5	0.1	0.25
M3	454	454	0.086	1.928	0.193	0.482	0.964	87.5	218.7
M2	2242	2696	0.511	1.248	0.125	0.312	0.624	336.4	841.0
M1	2582	5278	1.000	1.000	0.100	0.250	0.500	527.8	1319.4
M0	727	6005	-	-	-	-	-	-	-

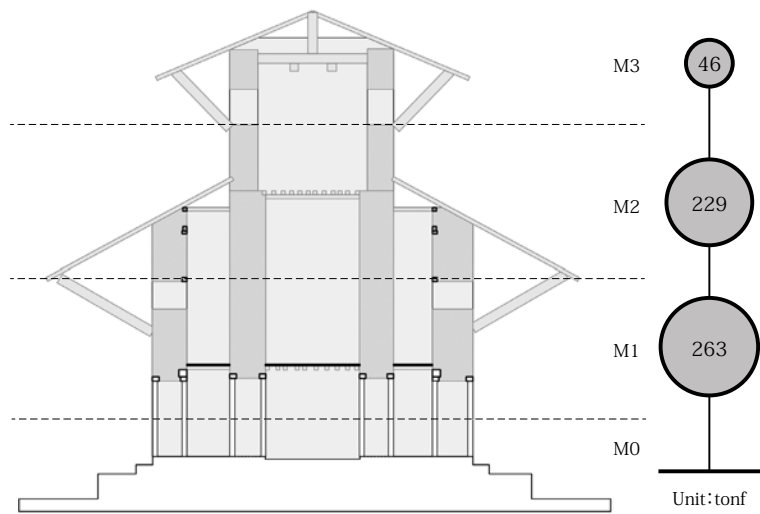


Fig.5-2-1 Mass point model weights for Jagannath Temple

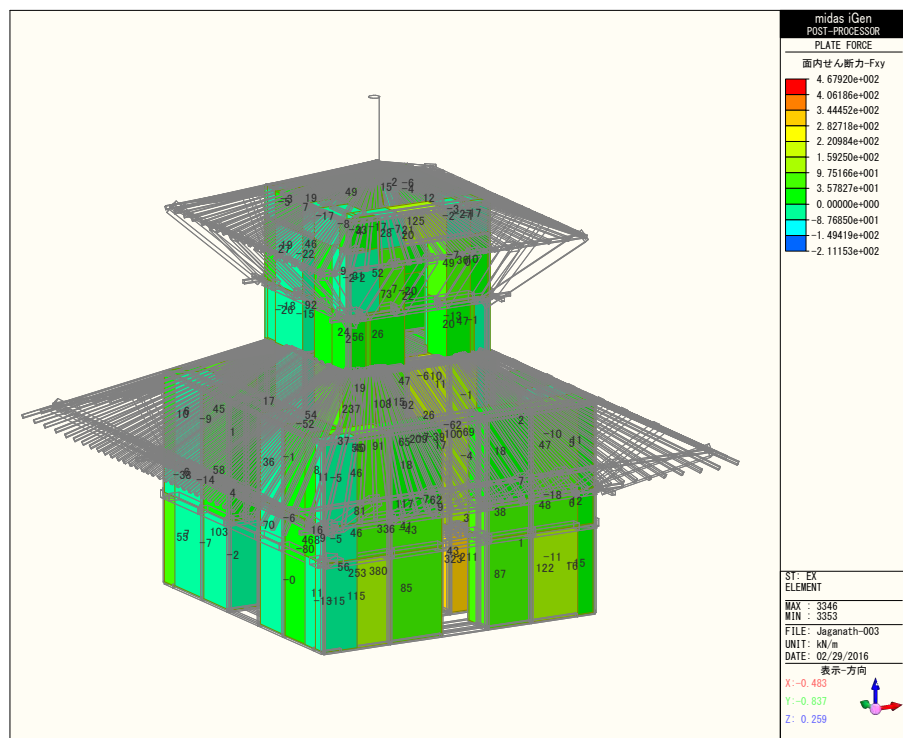


Fig.5-2-2 Shear force distribution (Cb=0.1)

Fig. 5-2-3 shows the calculation result for the distribution of compressive force of each wall in each storey for vertical load. The number in the figure shows the weight at one-fourth of the plan. The number in the left shows the weight of its story (w_j), and right shows the weight which that story sustains (Σw_j).

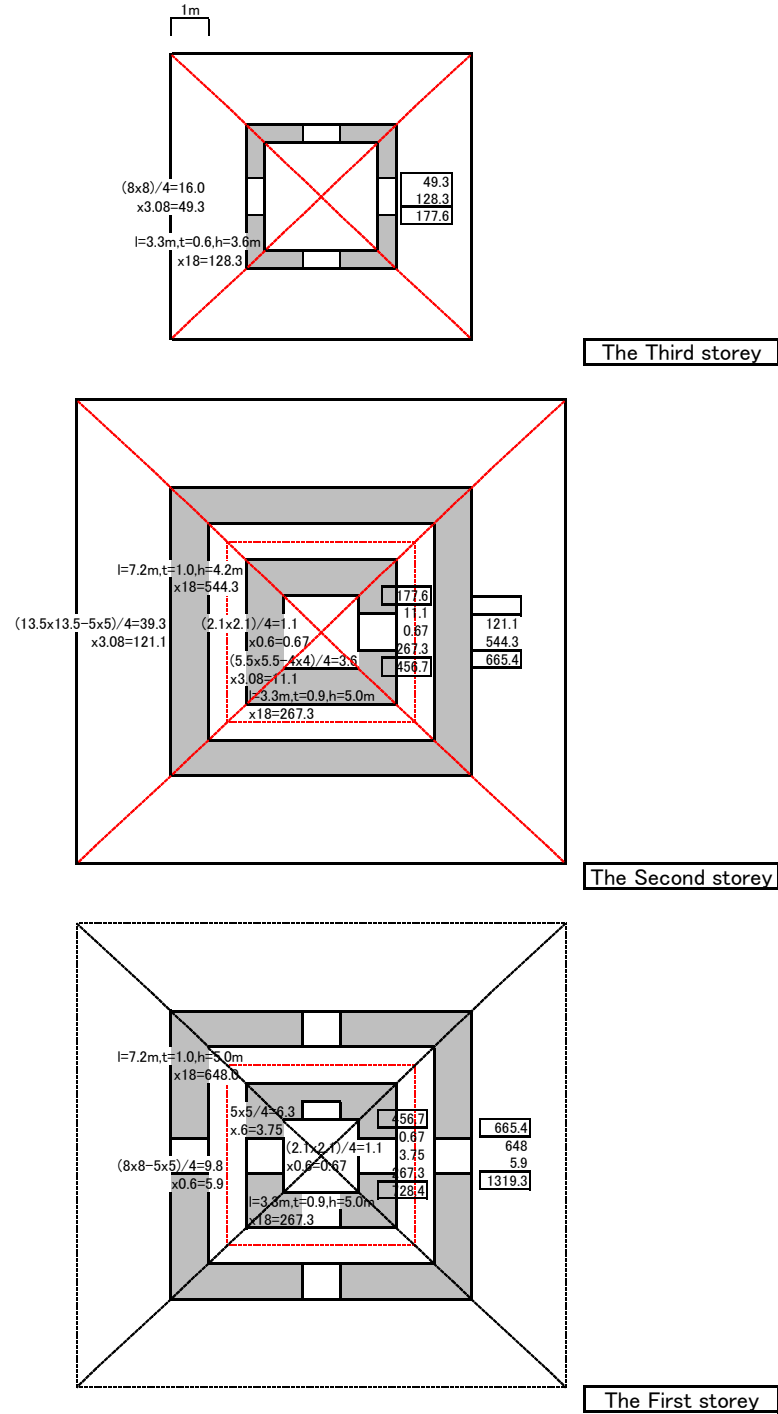


Fig.5-2-3 Distribution of compressive force for vertical load (Left: w_j , Right: Σw_j) of Jagannath Temple

Table 5-2-3 shows the shear force, assuming elastic response, calculated by area of walls in each storey, each direction and A_i distribution.

The shearing strength of brick wall is estimated by former experiments as $F_s = 0.15$ [N/mm²] when ignoring the compressive force and evaluate only the joint, or $F_s = 0.0867 + 0.9\sigma$ [N/mm²] when concerning the compressive force. It is assumed as $\mu = 0.5$ when not evaluating mortal joints but estimating friction resistance.

It is confirmed that the shear force does not exceed the allowable shearing stress when $C_b = 0.25$, namely the input acceleration on the ground surface = $0.25G$.

Concerning the top storey whose damage by the earthquake is heavy, assuming the elastic response, the shear force on top storey exceeds its allowable shearing stress intensity when the input acceleration on the ground surface equals to the following value.

Concerning compressive force: $744.5 / 218.5 = 3.40$, $0.25 \times 3.40 = 0.85 G$

Ignoring compressive force: $0.150 / 0.045 = 3.33$, $0.25 \times 3.33 = 0.83 G$

The shear force on the first storey exceeds its allowable shearing stress when the input acceleration on the ground surface equals to the following value.

Concerning compressive force: $4854.8 / 1319.4 = 3.68$, $0.25 \times 3.68 = 0.92 G$

Ignoring compressive force: $0.150 / 0.096 = 1.56$, $0.25 \times 1.56 = 0.39 G$

In case ignoring the performance of brick joint and concerning friction resistance, it is estimated that the seismic performance ascends to resist against $0.4G$ of ground surface acceleration by using accurate brick joints.

Although the effect of compressive force on allowable shearing stress is large, confirmation of performance in actual specification is required.

Tab.5-2-3 Shearing stress of walls (Jagannath Temple)

Storey	Direction	Wall length L (m)	Wall thickness t (m)	Number	Cross-section area (m ²)	Total wall cross-section area (m ²)	Vertical load (kN)	Shear force Q (kN)	Shearing stress intensity τ (N/mm ²)	Compressive stress intensity σ_c (N/mm ²)	Allowable shearing stress intensity		Allowable shear force with compression	
											Without compression	With $0.0867 + 0.9\sigma_c$	Each wall (kN)	Each storey (kN)
3rd storey	NS	3.500	0.700	1	2.45	4.90	177.6	218.7	0.045	0.072	0.150	0.152	372	744.5
		3.500	0.700	1	2.45					0.072	0.150	0.152	372	
	EW	3.500	0.700	1	2.45	4.90	177.6	218.7	0.045	0.072	0.150	0.152	372	744.5
		3.500	0.700	1	2.45					0.072	0.150	0.152	372	
2nd storey	NS	7.200	0.850	1	6.12	18.74	665.4	841.0	0.045	0.109	0.150	0.185	1129	3644.5
		7.200	0.850	1	6.12					0.109	0.150	0.185	1129	
		3.250	1.000	1	3.25					0.141	0.150	0.213	693	
		3.250	1.000	1	3.25					0.141	0.150	0.213	693	
		7.250	1.000	1	7.25					0.092	0.150	0.169	1227	
	EW	7.250	1.000	1	7.25	19.86	665.4	841.0	0.042	0.092	0.150	0.169	1227	3741.2
		3.150	0.850	1	2.68					0.171	0.150	0.240	643	
		3.150	0.850	1	2.68					0.171	0.150	0.240	643	
		6.050	0.90	1	5.45					0.242	0.150	0.305	1659	
		6.050	0.90	1	5.45					0.242	0.150	0.305	1659	
1st storey	NS	2.000	0.70	1	1.40	13.69	718.4	1319.4	0.096	0.513	0.150	0.549	768	4854.8
		2.000	0.70	1	1.40					0.513	0.150	0.549	768	
		6.050	0.90	1	5.45					0.242	0.150	0.305	1659	
		6.050	0.90	1	5.45					0.242	0.150	0.305	1659	
	EW	2.000	0.70	1	1.40	13.69	718.4	1319.4	0.096	0.513	0.150	0.549	768	4854.8
		2.000	0.70	1	1.40					0.513	0.150	0.549	768	
		6.050	0.90	1	5.45					0.242	0.150	0.305	1659	
		6.050	0.90	1	5.45					0.242	0.150	0.305	1659	

5.3. Seismic performance of Gopinath Temple

Fig. 5-3-1 shows the weight of each mass point in Gopinath Temple analysis model. Again, rooftop pinnacles, small openings, and wall thickness differences were ignored in the weight calculation. Table 5-3-2 lists the A_i distribution obtained from this weight calculation.

Again assuming that the A_i distribution is equal to the acceleration distribution, an input acceleration of 0.25 G ($C_1 = 0.25$) resulted in an output acceleration at the top storey of 0.472 G. Output acceleration may again exceed 0.5 G if the external force is larger than the friction resistance of the brick wall joints at the top storey.

This assumption corresponds with the field survey results for Gopinath Temple that noted earthquake damage concentrated at the first storey. A similar tendency is likely observed for buildings with upper storey walls that do not continue straight to the first storey or with smaller cross-sectional brick wall areas at the lower storey compared with the upper storey cross-sectional areas.

Tab.5-3-1 Estimated building weight of Gopinath Temple

Storey of mass	Position	Elements	a (m)	b (m)	t (m)	Unit (kN/m ²)	Modulus	Weight (kN)			Mass (tonf)
								Elements	Position	Storey	
M4	Roof of Upper	Roof tiles	4.80	4.80	1.00	2.4	1.2	66			
		Roof Truss	4.80	4.80	1.00	0.2	1	5	71		
	Wall		1.40	5.80	0.50	18	1	73	73	144	15
M3	Roof of Lower Floor	Wall	1.40	5.80	0.50	18	1	73	73		
		Roof tiles	7.00	7.00	1.00	2.4	1.2	141			
		Roof Truss	1.90	1.90	1.00	2.4	-1.2	-10	131		
			7.00	7.00	1.00	0.2	1	10			
	Floor		2.00	2.00	1.00	0.2	-1	-1	9		
		Floor beams	2.00	2.00	1.00	0.6	1	2	2		
		Wall Inner						0			
M2	Wall	Outer	1.10	12.00	0.60	18	1	143	143	358	37
		Inner						0			
	Floor	Outer	1.10	12.00	0.60	18	1	143	143		
		Floor beams	3.60	3.60	1.00	0.6	1	8	8		
	Wall	Inner Opening	1.75	12.00	0.60	18	1	227			
		Outer Opening	0.75	20.40	0.35	18	1	96	323		
	Roof of Lower Floor	Roof tiles	9.40	9.40	1.00	2.4	1.2	254			
		Roof Truss	3.60	3.60	1.00	2.4	-1.2	-37	217		
			9.40	9.40	1.00	0.2	1	18			
			3.60	3.60	1.00	0.2	-1	-3	15	706	72
M1	Wall	Inner Periphery Opening	1.75	12.00	0.60	18	1	227			
		Outer Periphery Opening	1.75	20.40	0.35	18	1	225			
		Roof Truss	8.00	8.00	1.00	0.2	1	13			
			5.40	5.40	1.00	0.2	-1	-6	459		
	Floor		5.60	5.60	1.00	0.6	1	19	19		
		Inner Opening	1.15	12.00	0.60	18	1	149			
		Outer columns	1.15	4.00	0.60	18.00	-1	-50			
									99	577	59
M0	Wall	Inner Opening	1.15	12.00	0.60	18	1	149			
		Columns in Outer Periphery	1.15	4.00	0.60	18.00	-1	-50			
									99	99	10
Total										1884	192

Tab.5-3-2 A_i distribution at each storey for Gopinath Temple

Storey	w_i (kN)	$W_i=\sum w_i$ (kN)	α_i W_i/W	A_i	C_i		Q_i		
					0.1	0.25	0.5	0.1	0.25
M4	144	144	0.081	1.886	0.189	0.472	0.943	27.2	67.9
M3	358	502	0.281	1.413	0.141	0.353	0.707	70.9	177.3
M2	706	1208	0.677	1.139	0.114	0.285	0.569	137.5	343.8
M1	577	1784	1.000	1.000	0.100	0.250	0.500	178.4	446.1
M0	99	1884	-	-	-	-	-	-	-

*Building height h ; 10.5m, Design first period T ; 0.21 [sec.] are assumed for calculation

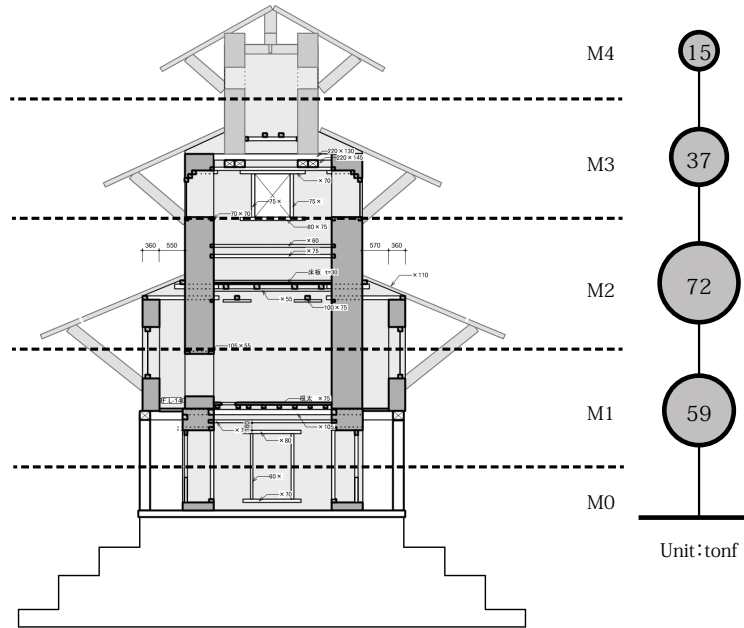


Fig.5-3-1 Mass point model weights for Gopinath Temple

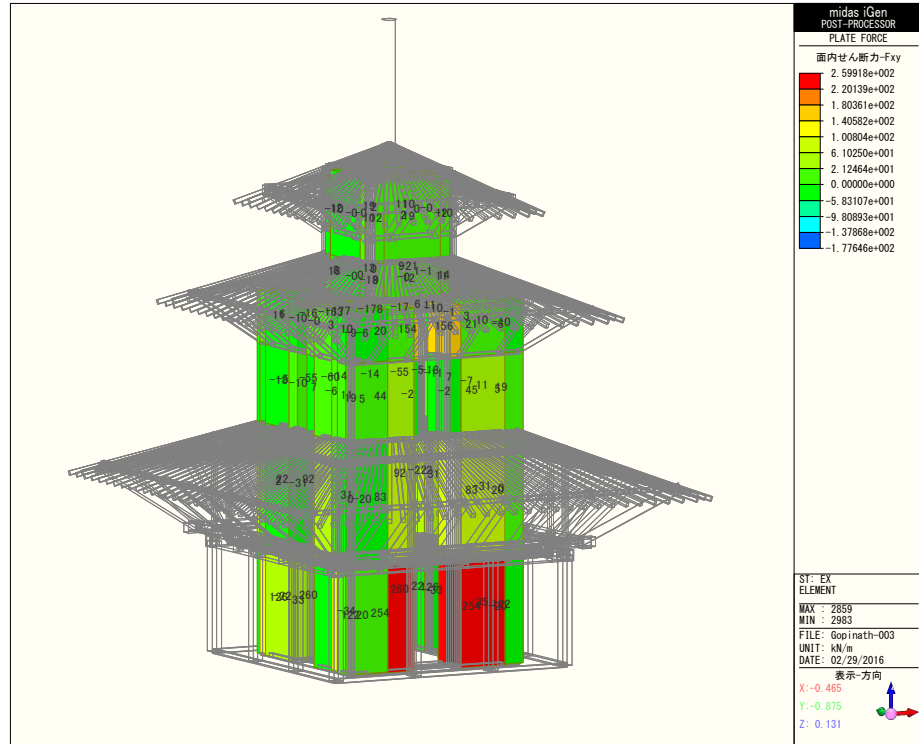


Fig.5-3-2 Shear force distribution ($C_b=0.1$)

Fig. 5-3-3 shows the calculation result for the distribution of compressive force of each wall in each storey for vertical load. The number in the figure shows the weight at one-fourth of the plan. The number in the left shows the weight of its story (w_j), and right shows the weight which that story sustains (Σw_j).

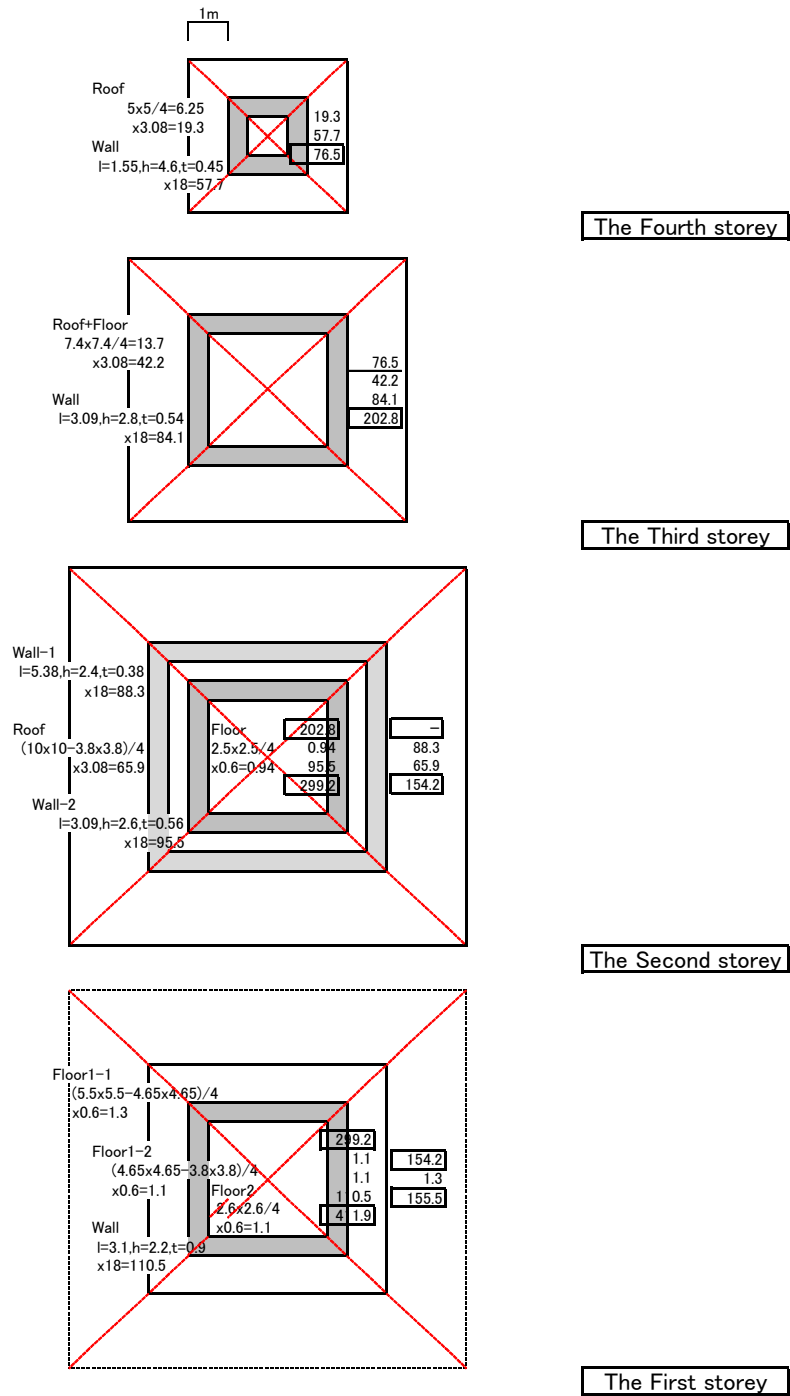


Fig.5-3-3 Distribution of compressive force for vertical load (Left: w_j , Right: Σw_j) of Gopinath Temple

Table 5-3-3 shows the shear force, assuming elastic response, calculated by area of walls in each storey, each direction and A_i distribution.

The shearing strength of brick wall is estimated by former experiments as $F_s = 0.15$ [N/mm²] when ignoring the compressive force and evaluate only the joint, or $F_s = 0.0867 + 0.9\sigma$ [N/mm²] when concerning the compressive force. It is assumed as $\mu = 0.5$ when not evaluating mortal joints but estimating friction resistance.

Concerning the top storey whose damage by the earthquake is heavy, assuming the elastic response, the shear force on top storey exceeds its allowable shearing stress intensity when the input acceleration on the ground surface equals to the following value.

Concerning compressive force: $1034.0 / 446.1 = 2.32$, $0.25 \times 2.32 = 0.58$ G

Ignoring compressive force: $0.150 / 0.132 = 1.14$, $0.25 \times 1.14 = 0.28$ G

The shear force on the first storey exceeds its allowable shearing stress when the input acceleration on the ground surface equals to the following value.

Concerning compressive force: $4854.8 / 1319.4 = 3.68$, $0.25 \times 3.68 = 0.92$ G

Ignoring compressive force: $0.150 / 0.096 = 1.56$, $0.25 \times 1.56 = 0.39$ G

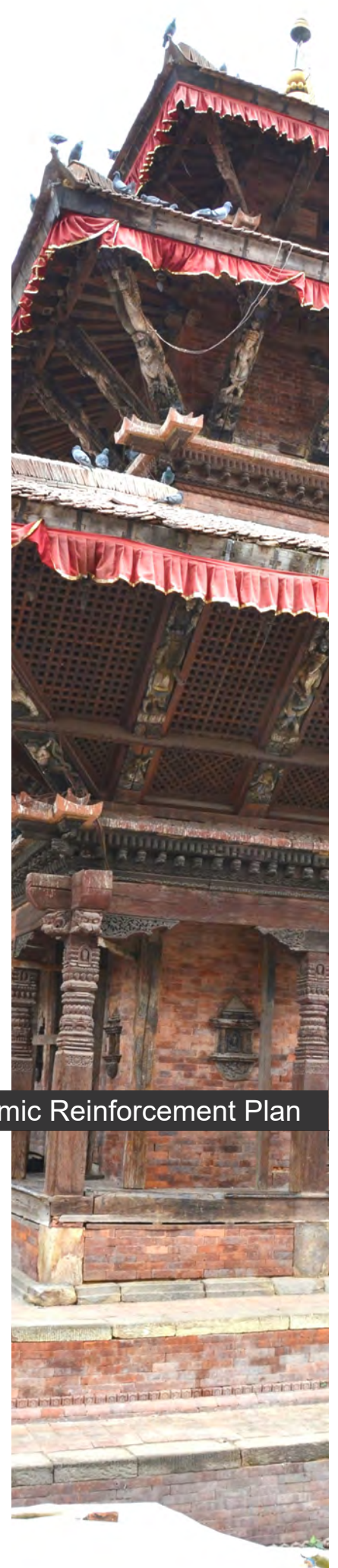
In case ignoring the performance of brick joint and concerning friction resistance, the response acceleration of the top storey is estimated to be close to 0.5G. Concerning this result, the shear force on top storey has possibility to exceed its allowable shearing stress when $C_b = 0.25$.

It is demonstrated that using proper brick joints in first and top storey is important for ascending seismic performance of whole building.

Although the effect of compressive force on allowable shearing stress is large, confirmation of performance in actual specification is required.

Tab.5-3-3 Shearing stress of walls (Gopinath Temple)

Storey	Direction	Wall length L (m)	Wall thickness t (m)	Number	Cross-section area (m ²)	Total wall cross-section area (m ²)	Vertical load (kN)	Shear force Q (kN)	Shearing stress intensity τ (N/mm ²)	Compressive stress σ_c (N/mm ²)	Allowable shearing stress intensity		Allowable shear force with compressive	
											Without compression	With Compression 0.0867+0.9 σ_c	Each wall (kN)	Each storey (kN)
4th storey	NS	1.60	0.40	1	0.64	1.28	76.5	67.9	0.053	0.120	0.150	0.194	124	248.7
		1.60	0.40	1	0.64	1.28	76.5	67.9	0.053	0.120	0.150	0.194	124	248.7
	EW	1.60	0.40	1	0.64	1.28	76.5	67.9	0.053	0.120	0.150	0.194	124	248.7
		1.60	0.40	1	0.64	1.28	76.5	67.9	0.053	0.120	0.150	0.194	124	248.7
3rd storey	NS	3.09	0.54	1	1.67	3.34	202.8	177.3	0.053	0.122	0.150	0.196	327	654.4
		3.09	0.54	1	1.67	3.34	202.8	177.3	0.053	0.122	0.150	0.196	327	654.4
	EW	3.09	0.54	1	1.67	3.34	202.8	177.3	0.053	0.122	0.150	0.196	327	654.4
		3.09	0.54	1	1.67	3.34	202.8	177.3	0.053	0.122	0.150	0.196	327	654.4
2nd storey	NS	5.38	0.36	1	1.94	8.98	154.2	343.8	0.038	0.080	0.150	0.158	307	1594.9
		5.38	0.36	1	1.94	8.98	154.2	343.8	0.038	0.080	0.150	0.158	307	1594.9
		3.58	0.66	1	2.36	9.36	299.2	343.8	0.037	0.127	0.150	0.201	474	1628.1
		4.16	0.66	1	2.75	9.36	299.2	343.8	0.037	0.109	0.150	0.185	507	1628.1
	EW	5.38	0.36	1	1.94	9.36	154.2	343.8	0.037	0.080	0.150	0.158	307	1628.1
		5.38	0.36	1	1.94	9.36	154.2	343.8	0.037	0.080	0.150	0.158	307	1628.1
		4.16	0.66	1	2.75	9.36	299.2	343.8	0.037	0.109	0.150	0.185	507	1628.1
		4.16	0.66	1	2.75	9.36	299.2	343.8	0.037	0.109	0.150	0.185	507	1628.1
1st storey	NS	2.41	0.70	1	1.69	3.37	411.9	446.1	0.132	0.244	0.150	0.306	517	1034.0
		2.41	0.70	1	1.69	3.37	411.9	446.1	0.132	0.244	0.150	0.306	517	1034.0
	EW	2.41	0.70	1	1.69	3.37	411.9	446.1	0.132	0.244	0.150	0.306	517	1034.0
		2.41	0.70	1	1.69	3.37	411.9	446.1	0.132	0.244	0.150	0.306	517	1034.0



6. Summary of the result and Seismic Reinforcement Plan

6. Summary of the result and Seismic Reinforcement Plan

6.1. Summary of the result

With regard to planning the preservation and restoration plan of historic buildings in Nepal, it is important to consider the following findings obtained in this structural survey:

- Structural drawings and analysis models for subject buildings can be developed from survey results that describe building dimensions and construction methods. Structural analysis can be performed after verifying the material characteristics of brick, mortar, and timber.
- Micro-tremor measurement can be used to estimate the natural frequency and vibration mode of a subject building.
- Through approximate estimation of seismic performance, brick wall joints can be damaged by an input acceleration of 0.25 G and the buildings incur concentrated damage either at the top or first storeys.

Most important for preservation planning and repair is to set realistic performance requirements (i.e. an acceptable degree of damage from an earthquake) and to regulate the building collapse mode to the extent possible. Future preservation planning and repair efforts can benefit from development of a detailed structural analysis model that includes accurate material characteristics. Preliminary assimilation of a material characteristics database using previously reported results for brick, mortar joints (existing and fresh), and timber elements (existing and fresh) is required.

6.2. Structural reinforcement plan

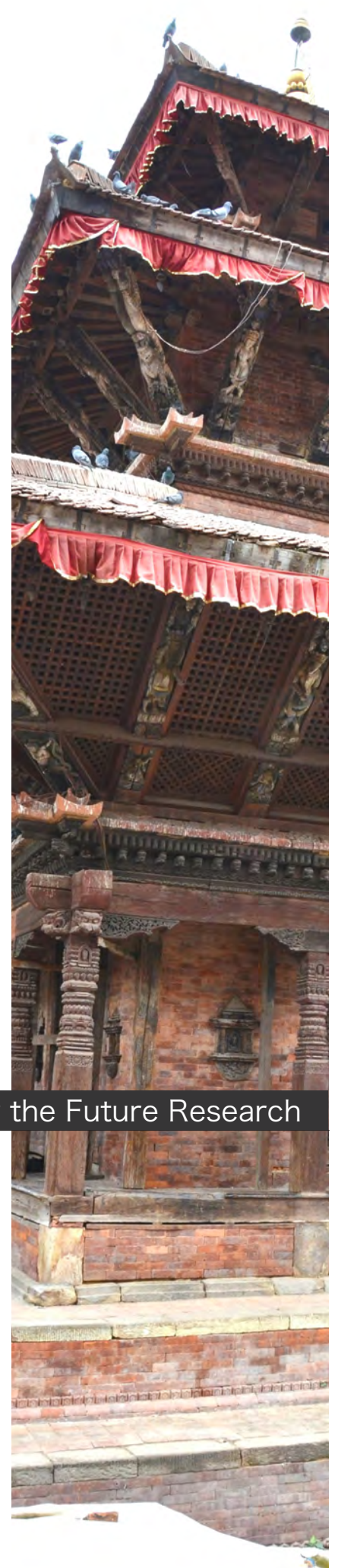
It is required to clarify the performance requirements including viewpoint as the followings for the structural reinforcement plan.

- Performance requirements, such as presumed earthquake, acceptable degree of damage from the earthquake and regulation of building collapse mode, are required to be set accurately.
- Some local engineers favour collapse mechanisms that allow reuse of bricks, viewing the removal of mortar and reuse of materials as a superior repair method. For preservation planning and repair, this requires prediction of the collapse mode of buildings and a method for valuing the building and its associated structural material.
- Bricks from a collapsed building are not always used to repair the original building. As such, reuse procedures must be coordinated among multiple projects.

Structural reinforcement, attaching importance to the preservation of bricks as shown above, is required to verify following points.

- To prevent a more devastating collapse, joint failure should precede brick failure. Strength and compounding adjustments for joint mortar may be required. Adjustments should be made according to both preservation planning and structural performance considerations.
- Timber frames may prevent total building collapse following brick wall failure. Historical transition and usage methods must be coordinated.
- Careful documentation of building characteristics and construction methods is important before and after building collapse. In this survey, the brick and timber-frame systems inside the walls were difficult to comprehend without detailed information.

Based on this structural survey and the observations noted above, the seismic performance of Jagannath and Gopinath Temples depends heavily on the performance of the mortar joints in the brick walls. To prevent a more devastating collapse from failure of the bricks, mortar performance should be designed to be lower than that of the brick itself to induce collapse from the joint. Further information is required regarding original timber elements; timber frames help to prevent total building collapse by resisting their own weight.



7. Issues for the Future Research

7. Issues for the Future Research

7.1. Collecting data for analysis

In the present report, we performed structural performance evaluation by abbreviated calculation, based on collected basic information of structural performance of multi-tiered tower. In order to comprehend the structural performance of individual buildings, further verification using specific values by performing detail calculation of building weight and collecting material characteristics of bricks, mortar joints and brick walls are required. (cf. 7.2. and 7.3.)

Moreover, with regard to restoration, it is required to perform seismic diagnosis to confirm the structural performance of the buildings before suffering earthquake, and to set performance requirements. On the occasion of setting performance requirements, presumption of the input seismic motion and degree of damage are important.

7.2. Structural tests on bricks

In order to comprehend the material characteristics of bricks and brick walls for structural analysis, it is desirable to perform structural tests below.

- (1) Compressive test of bricks and joint mortar
- (2) Combined test against vertical and lateral force
- (3) Bending test

The structural performance of brick wall is decided mainly by that of brick itself and mortar joint. Therefore, in order to comprehend the structural performance of building both before and after suffering earthquake, it is required to understand the performance of both present and new bricks, and both existing joint and newly filled joint. The examples of specification of joint mortar, specimens and experimental method are shown below.

Specifications of mortar for mesonry joint in the specimen for the tests

- (1) Existing mortar from the damaged structure [Curing Period: 1 month]
- (2) Yellow mud (traditional) [Curing Period: 1 month]
- (3) Lime Surkhi 1 (Lime: Surkhi (Brick dust): Sand = 1:1:3) [Curing Period: 2 month]
- (4) Lime Surkhi 2 (Lime: Surkhi (Brick dust): Sand = 1:1:1) [Curing Period: 2 month]

<Method of the structural test>

Compressive test : 3 specimens for each mortar (12 specimens in total)

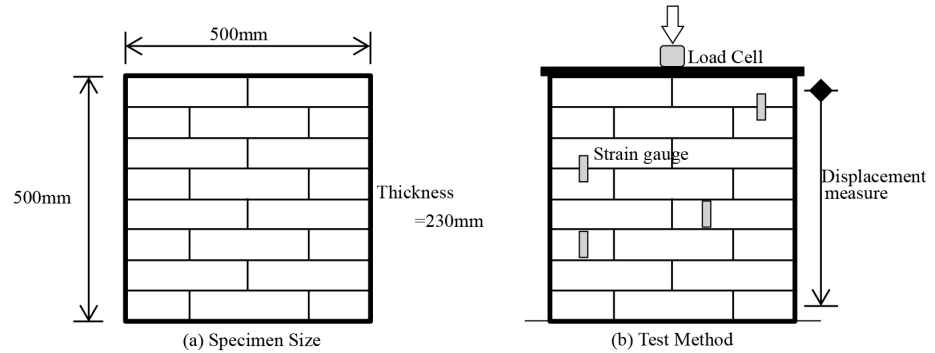


Fig.7-2-1 Compressive test

Combined test by using Steel Frame: 6 specimens for each mortar (24 specimens in total)

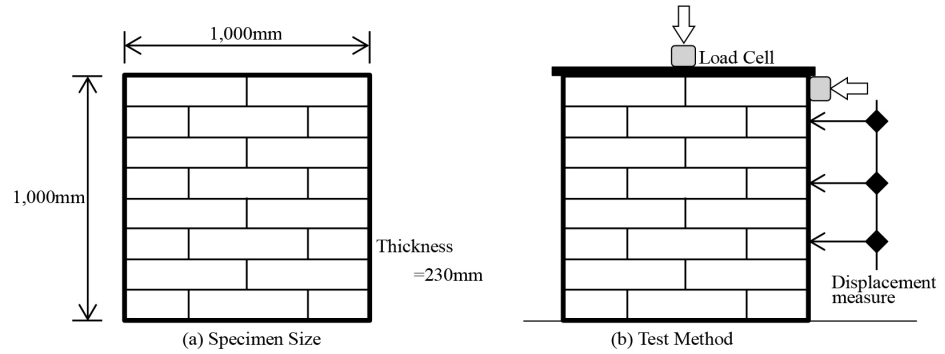


Fig.7-2-2 Combined test

Bending test: 3 specimens for each mortar (12 specimens in total)

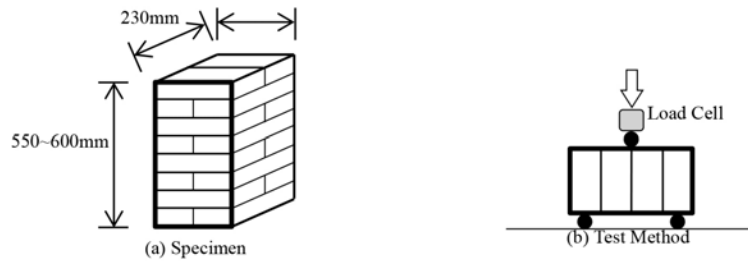


Fig.7-2-3 Bending test

Compressive test of mortar: 3 specimens for each mortar (12 specimens in total)

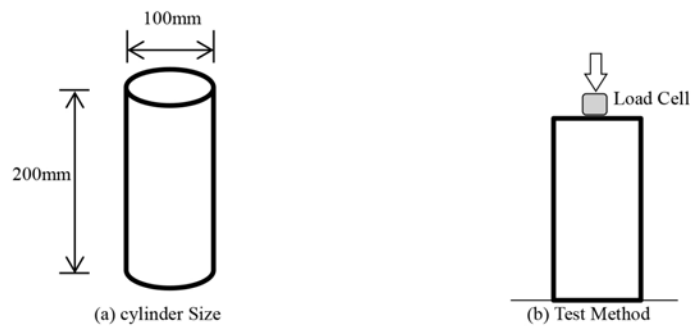


Fig.7-2-4 Compressive test of mortar



(1) Loading device 1
Pic.7-2-1 Loading devices



(2) Loading device 2

7.3. Structural Test on timber

The material characteristics of timber are important to comprehend the performance of timber frame. The following two species are supposed to be used in present buildings including Jagannath and Gopinath Temples.

Agrak (Sal): Timber for main frame
Salla (Pine): Timber not for structure and design(Using at hidden part)

The material characteristics (shown below) of these species are required to be comprehended.

Young's modulus: E (Compression, Bending, Embedding)

Material strength: F

Density: ρ

Examples of specimens and Testing method and Specimensize are shown below.

- Testing Method:

Bending Test, Compression Test

- Specimen size:

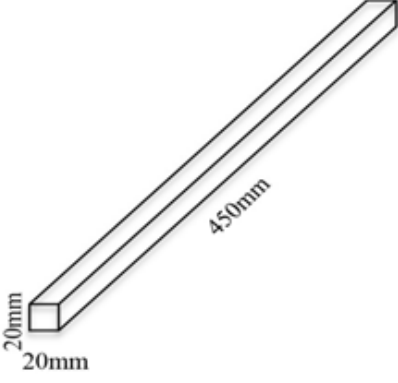
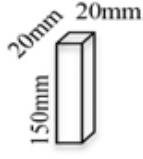
Bending Test: Breadth: 20mm, Depth: 20mm, Length: 450mm

Sustaining span: larger than $18d=360\text{mm}$

Compression Test: Breadth: 20mm, Depth: 20mm, Length: 150mm

Length: larger than $6d=120\text{mm}$

Tab.7-2-1 Specimen size for the Structural tests on timber

		Bending Test		Compression Test	
					
Size	Breadth: b	20mm		20mm	
	Depth: d	20mm		20mm	
	Length: l	450mm		150mm	
Species		Agrak(Sal)	Sala(Pine)	Agrak(Sal)	Sala(Pine)
Number		n=10	n=10	n=20	n=20

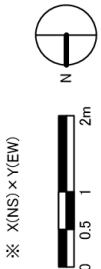
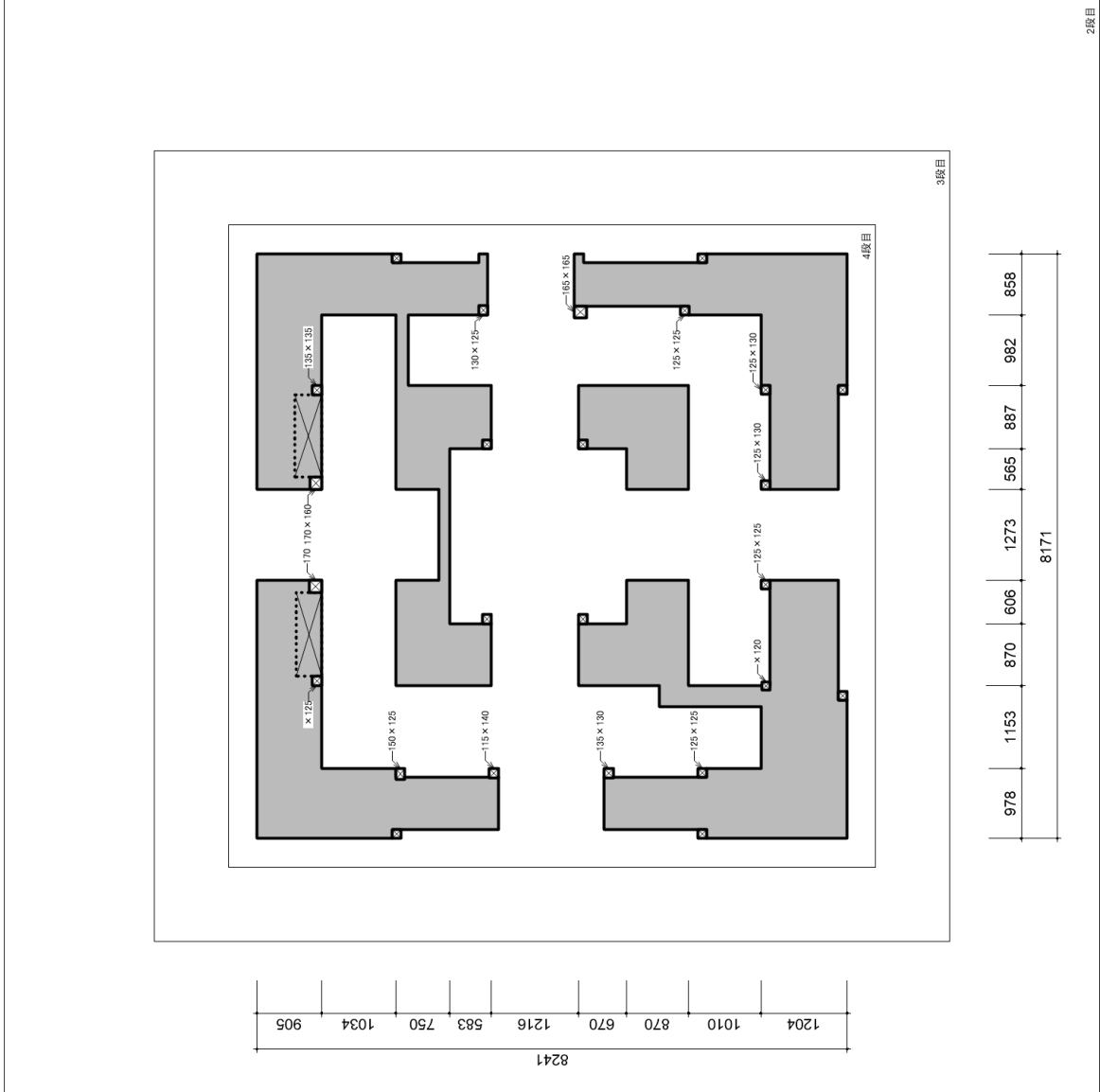
Appendix

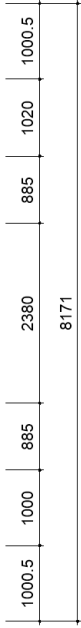
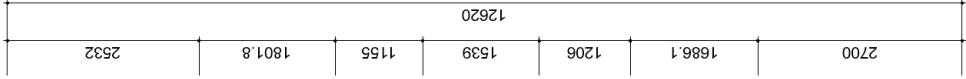
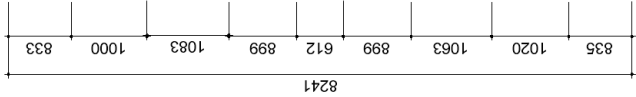
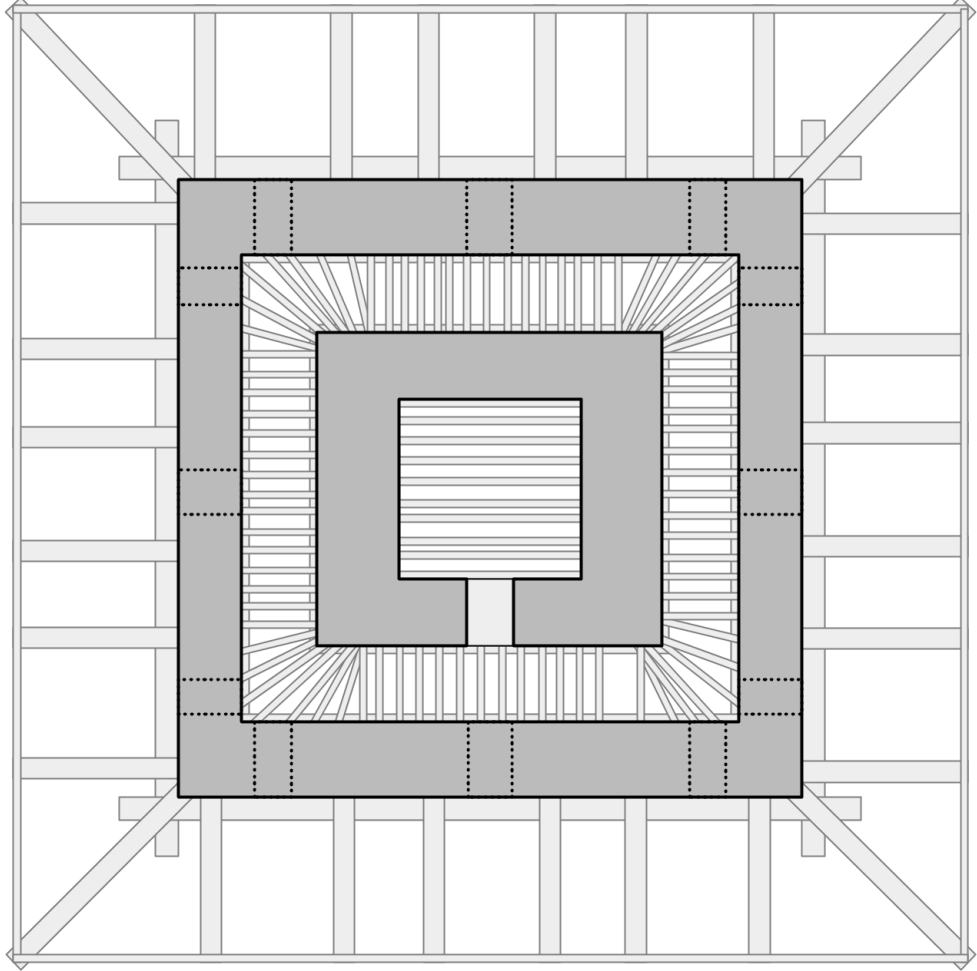
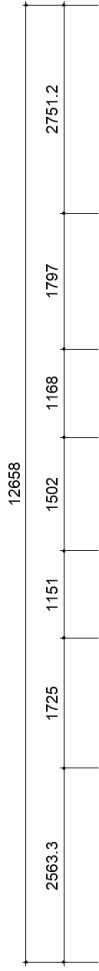
The structural drawings

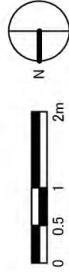
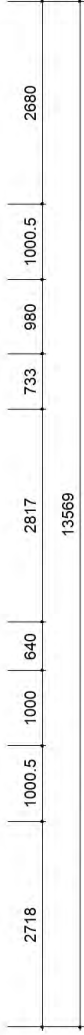
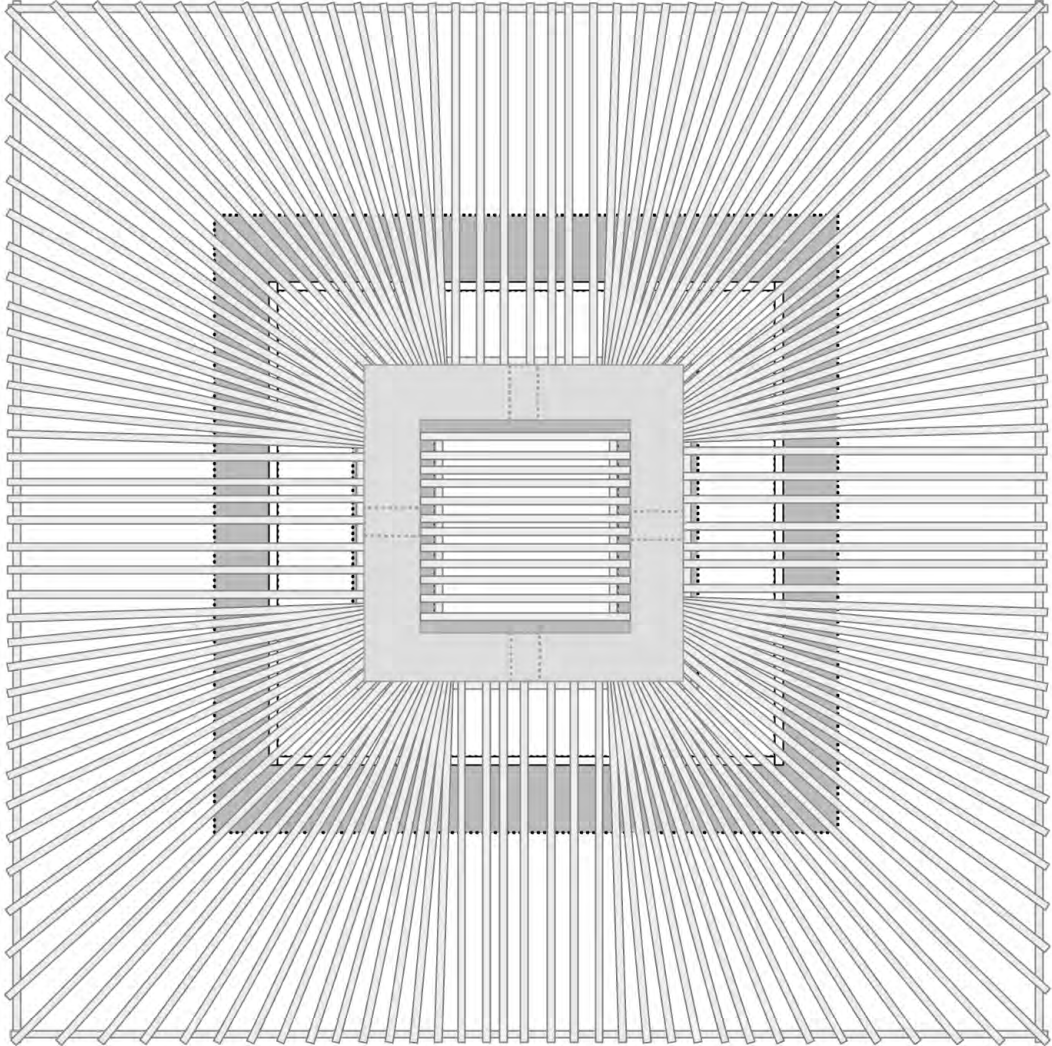
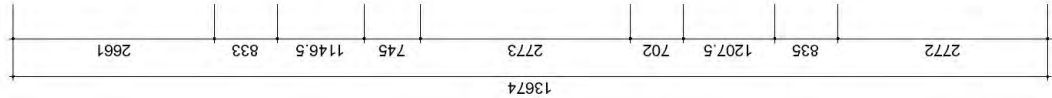
J01~J11	Jagannath Temple
G01~G17	Gophinath Temple

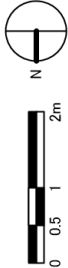
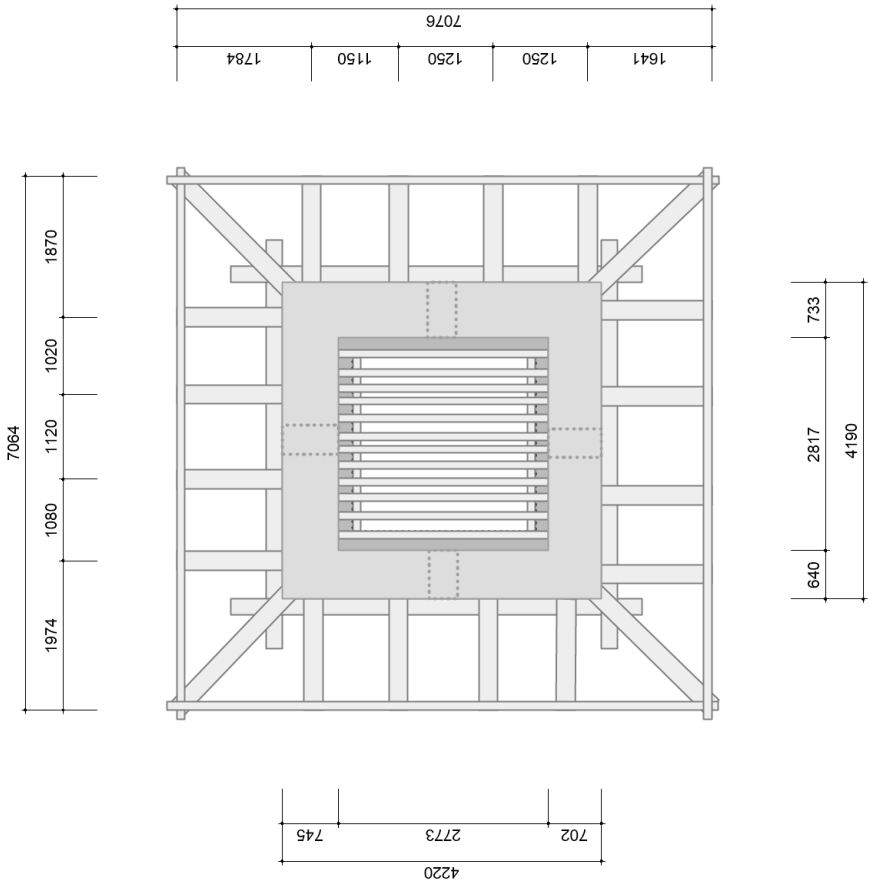
The structural drawings of Jagannath Temple

- J01 : Floor plan of pillars and wall, 1st storey
- J02 : Plan of struts of the 1st tier and joists, 2nd storey
- J03 : Plan of rafters of the 1st tier
- J04 : Plan of struts of the 2nd tier and joists, 3rd storey
- J05 : Plan of ridge beams, 3rd storey
- J06 : Plan of rafters of the 2nd tier
- J07 : North elevation
- J08 : East elevation
- J09 : West elevation
- J10 : South elevation
- J11 : Section of X (NS) direction
- J12 : Section of Y (EW) direction
- J13 : Size of bricks

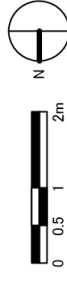
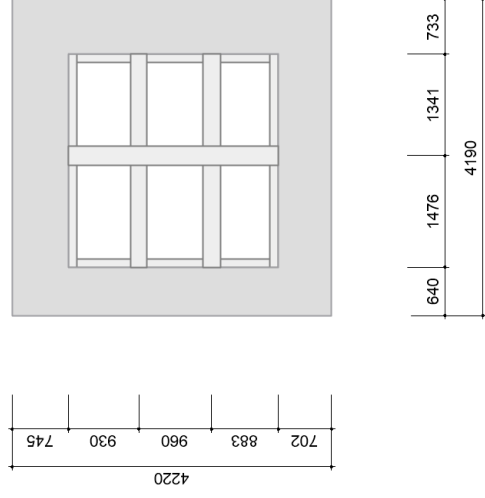




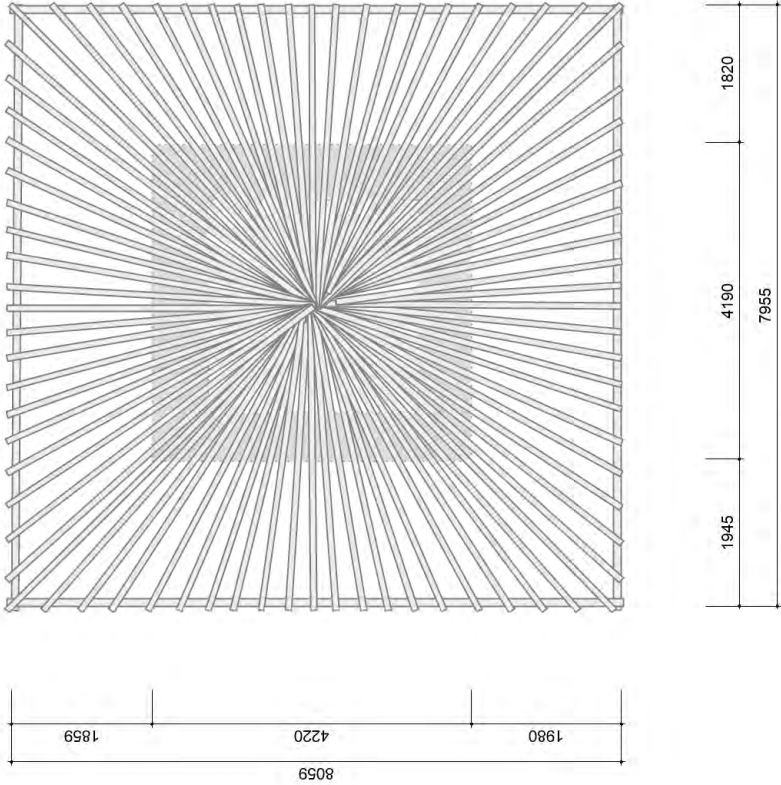




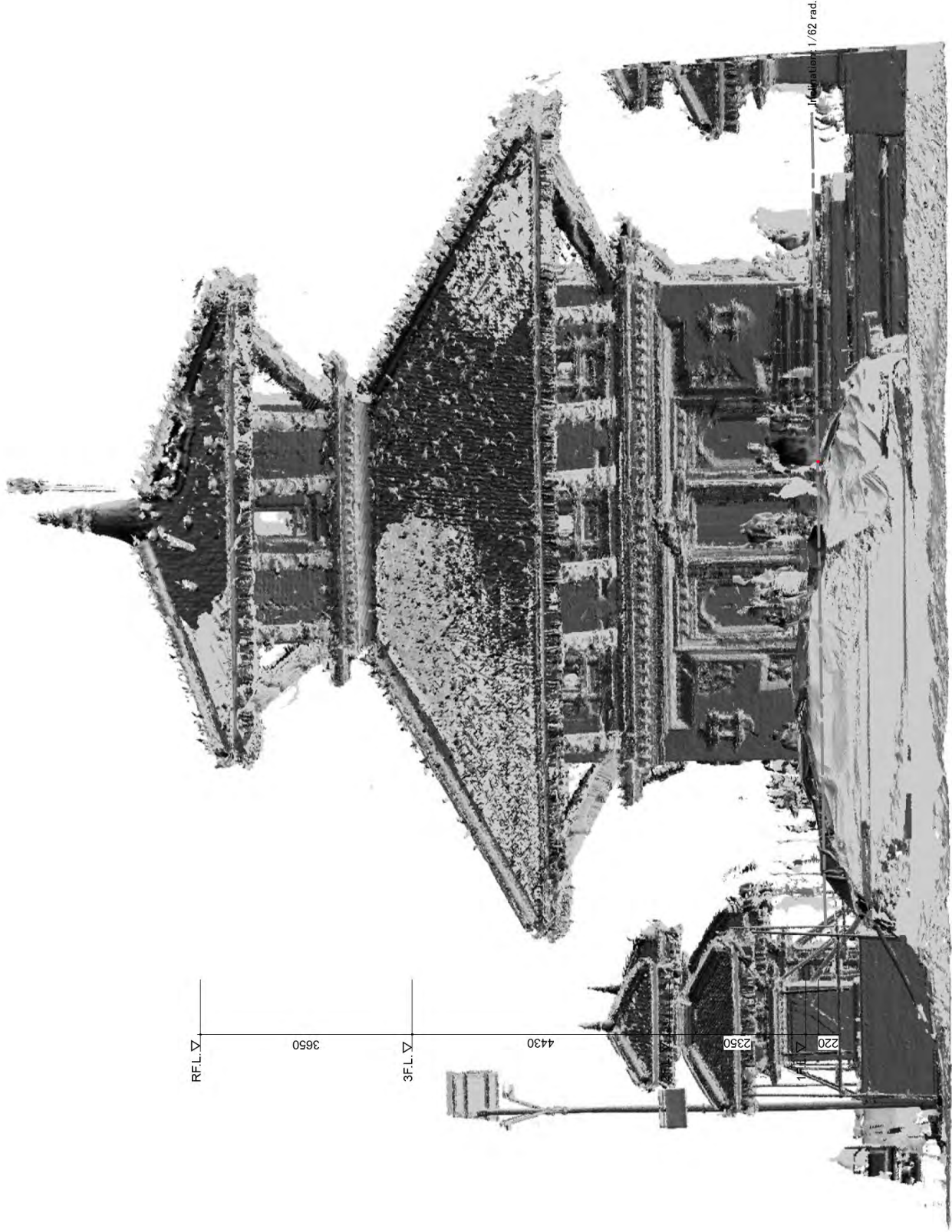
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	Name		Jagannath Temple		Day of Research		30 – Nov –2015
	Drawing Title		Plan of struts of the second tier and joists, third storey		Researcher		Koshihara lab
			Scale		1:100 (A4)		



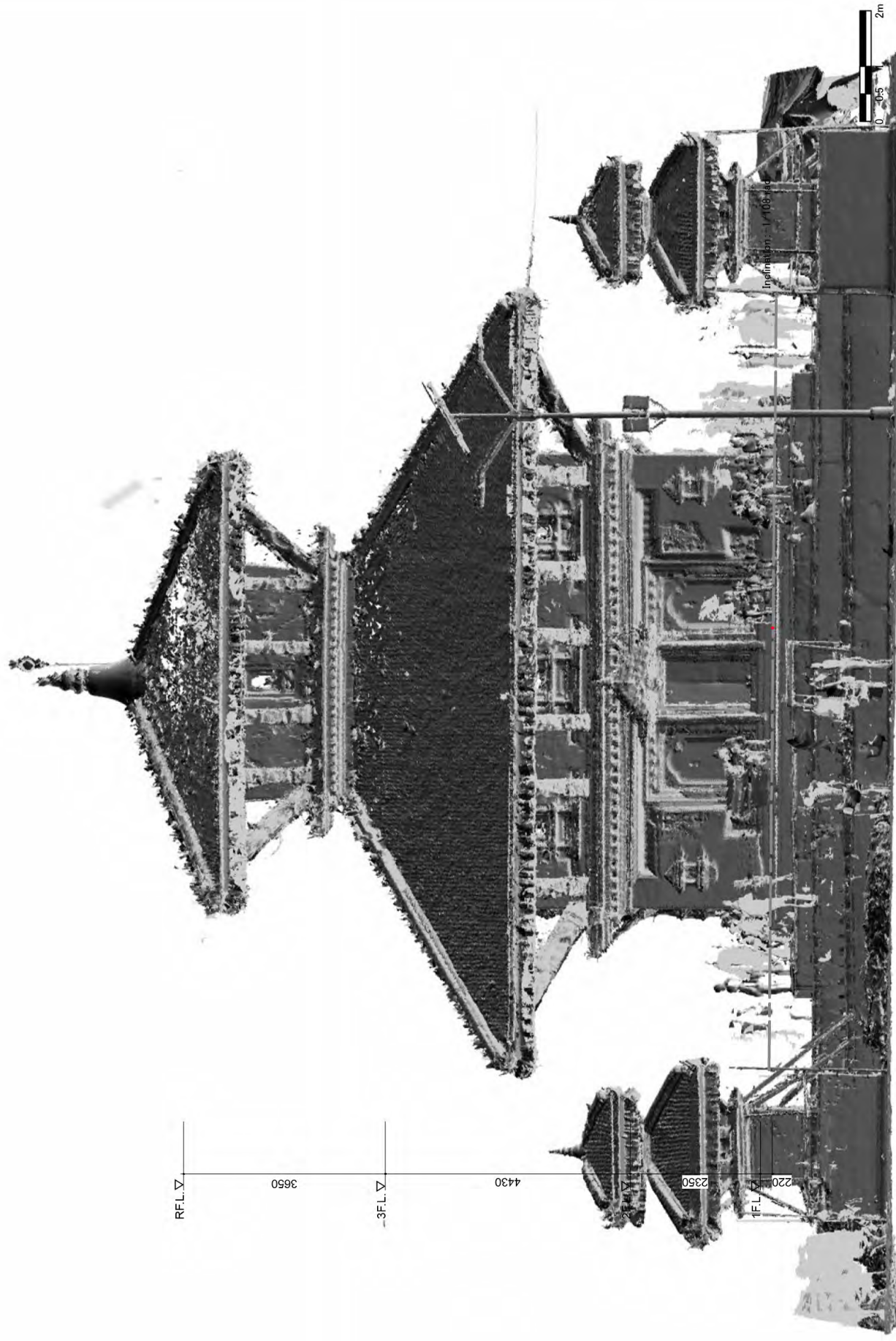
Project Title	Project for investigation of damage situation of cultural heritage in Nepal		J05
	Name	Jagannath Temple	
	Drawing Title	Plan of ridge beams, third storey	
		Scale	1:100 (A4)
		Day of Research	30 – Nov –2015
		Researcher	Koshihara lab



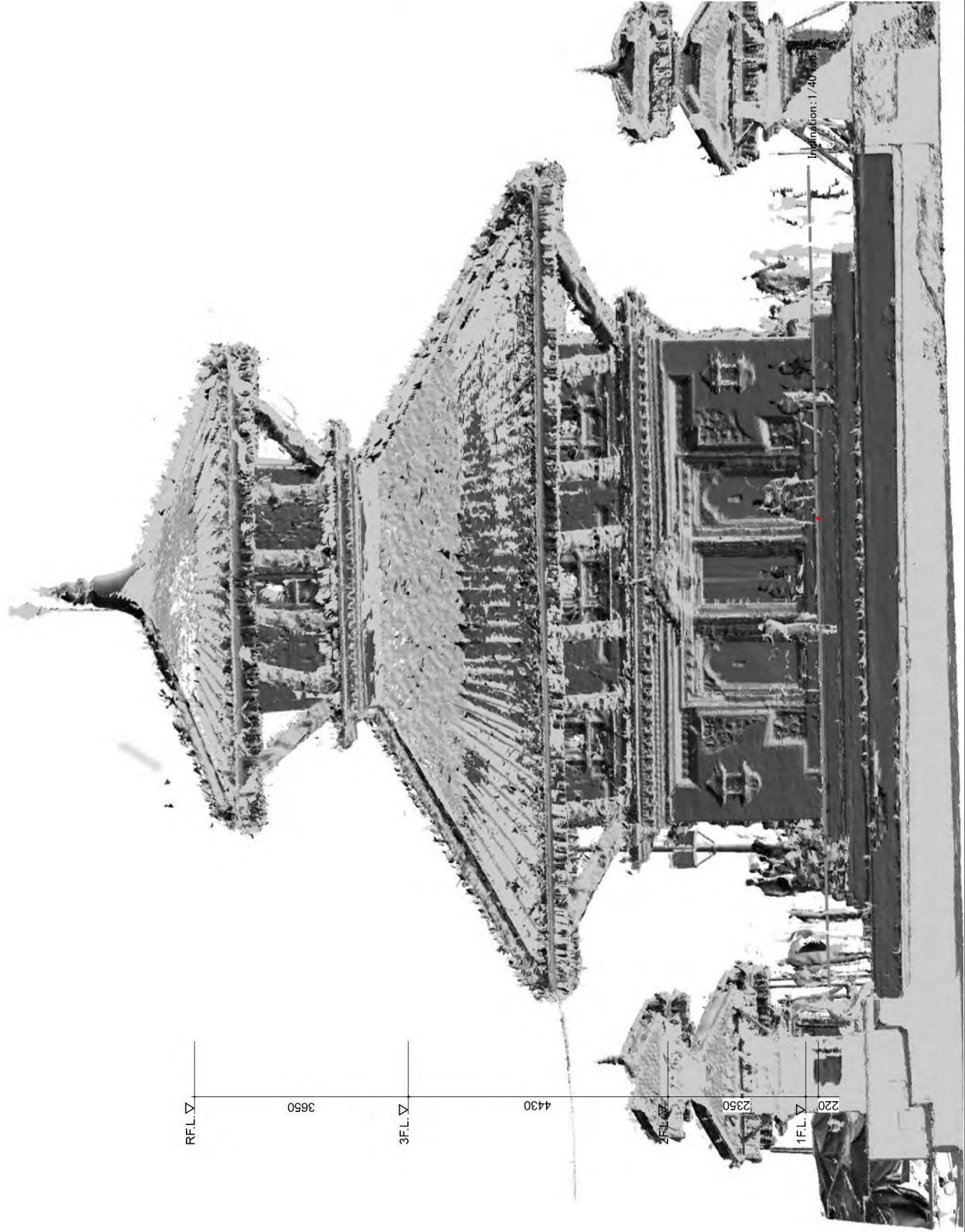
Project Title	Project for investigation of damage situation of cultural heritage in Nepal		Name		Jagannath Temple		Day of Research		30 – Nov –2015		J06
			Drawing Title		Plan of rafters of the second tier		Researcher		Koshihara lab		
							Scale		1:100 (A4)		

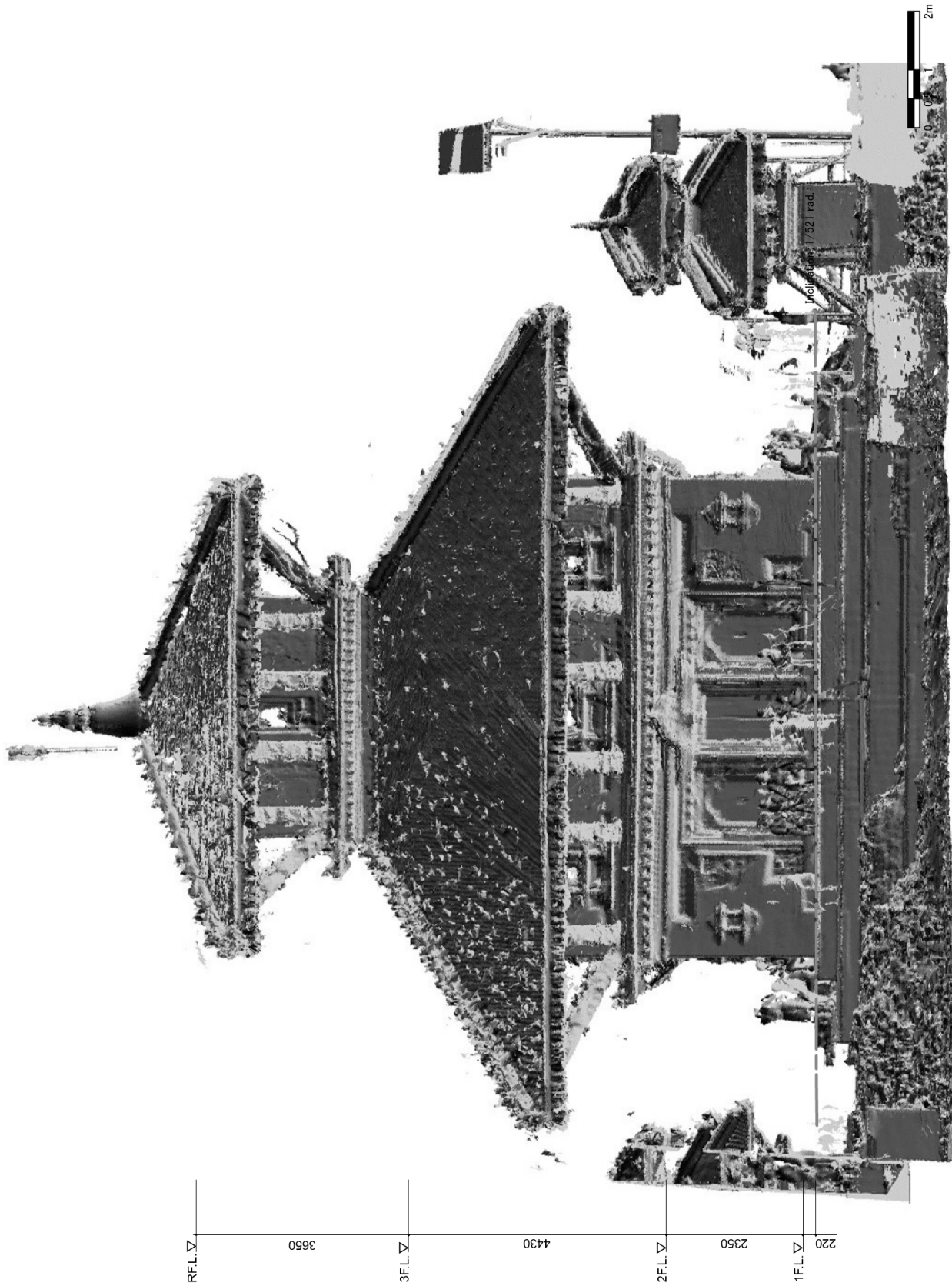


Project Title	Project for investigation of damage situation of cultural heritage in Nepal		Name		Jagannath Temple	Day of Research		30 - Nov -2015	J07
	Drawing Title		Scale		1:100 (A4)	Researcher		Koshihara lab	

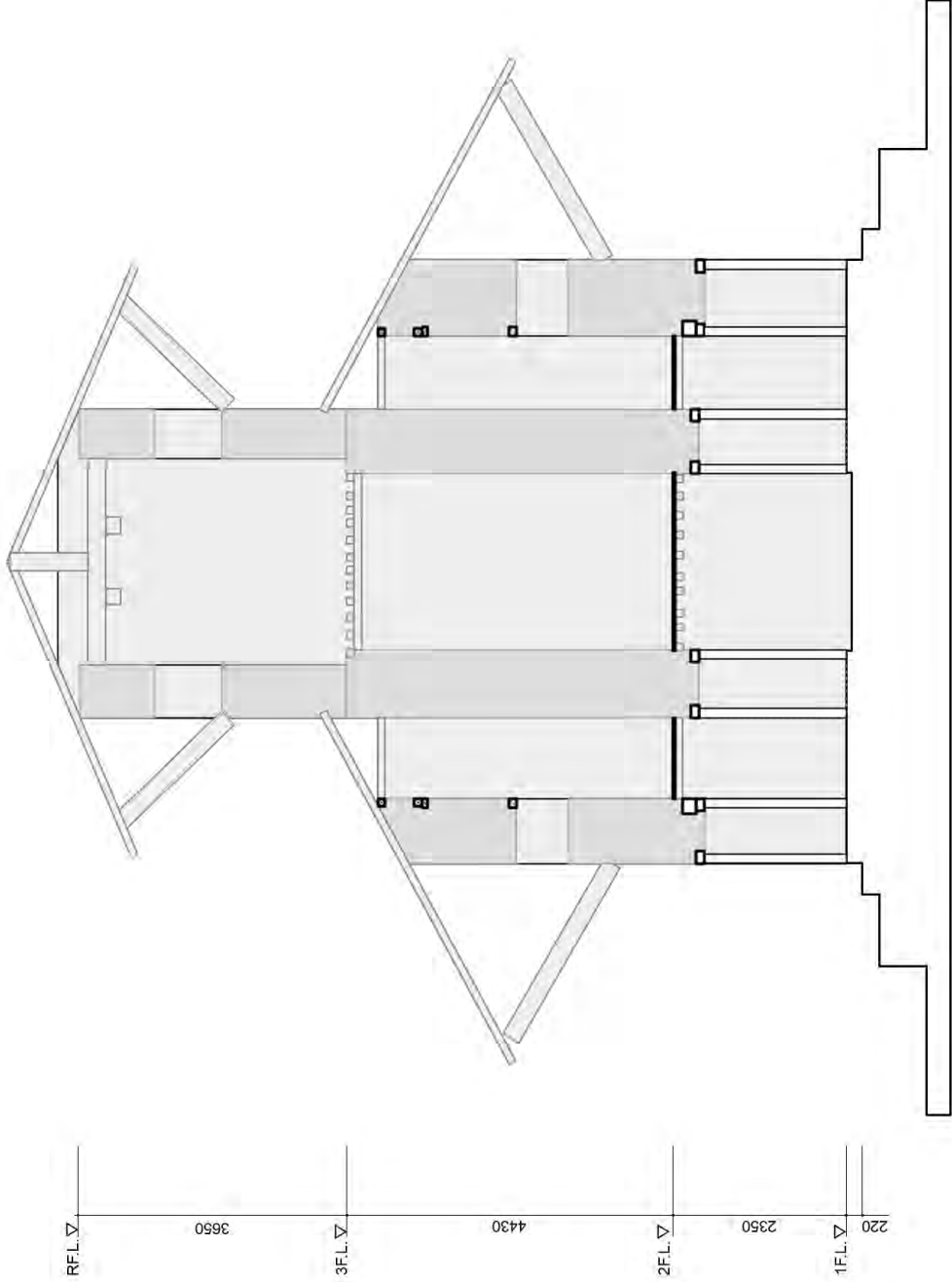


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	situation of cultural heritage in Nepal			Drawing Title	East Elevation		Researcher	Koshihara lab		

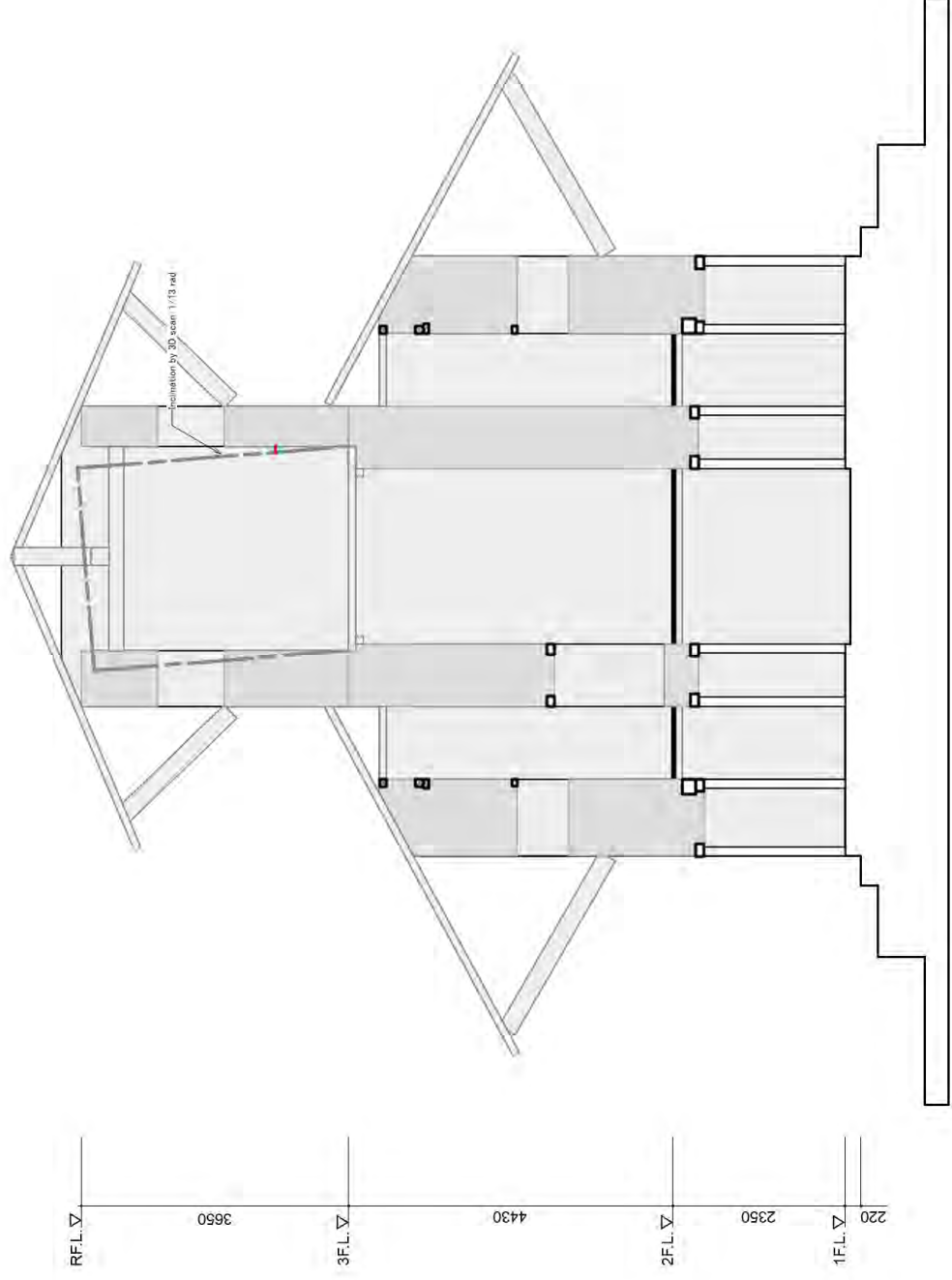




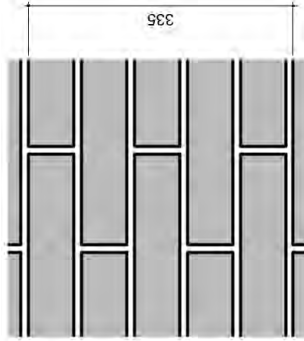
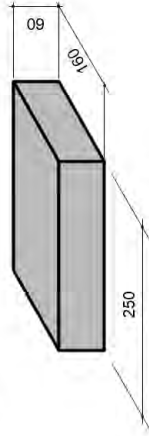
Project Title	Project for investigation of damage situation of cultural heritage in Nepal			Name	Jagannath Temple		Day of Research	30 – Nov –2015		J10
	Drawing Title			South Elevation		Scale	1:100 (A4)		Researcher	Koshihara lab



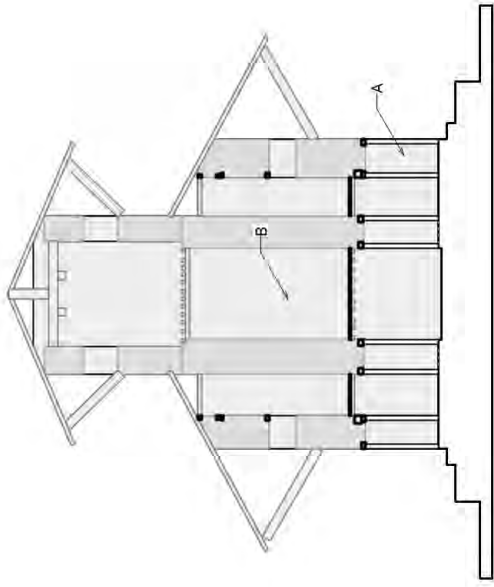
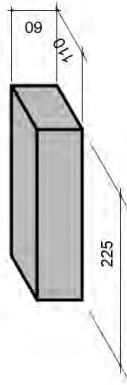
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	Drawing Title		Section-X(NS)		Scale		1:100 (A4)		Researcher		Koshihara lab	



A: 1st floor

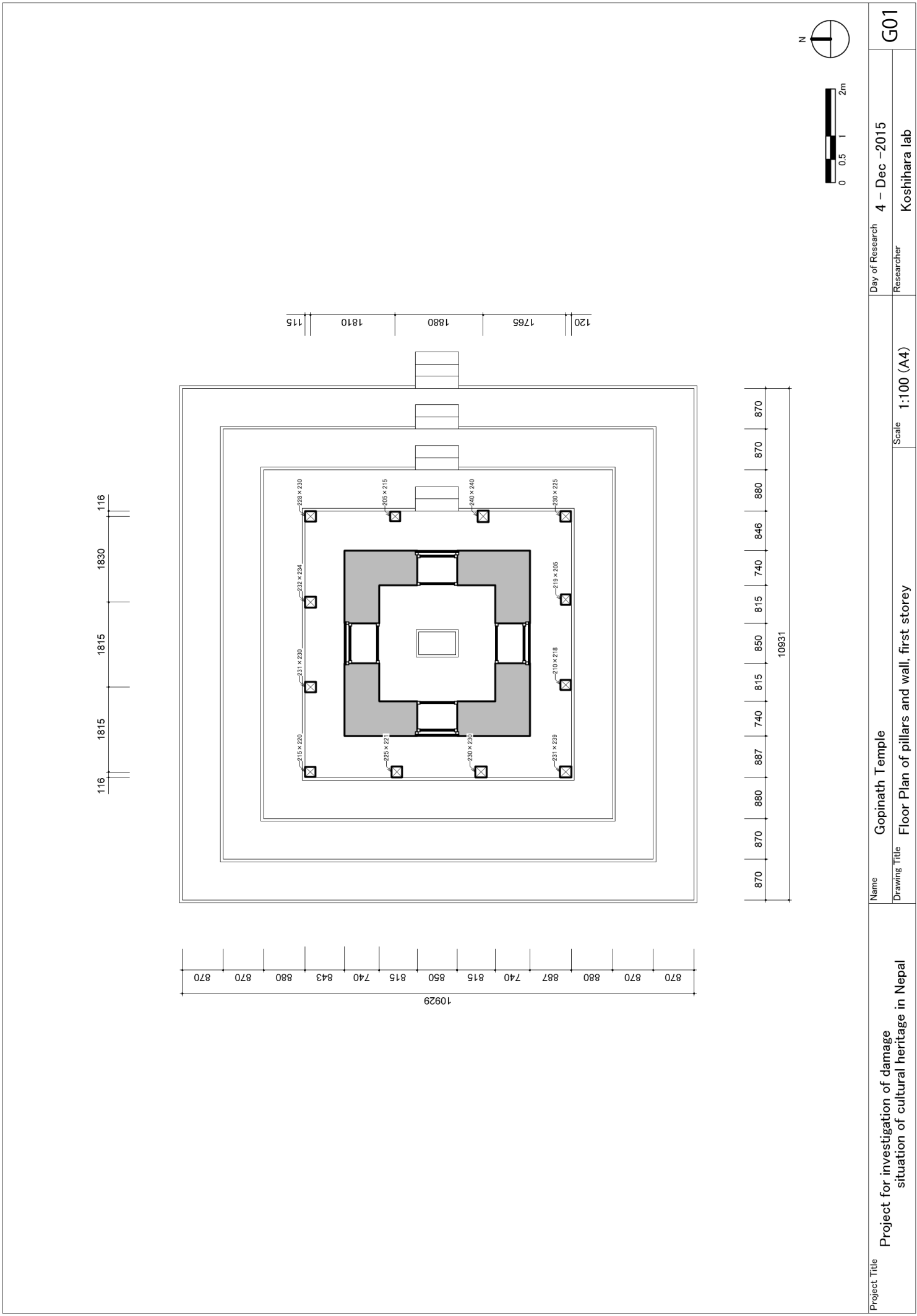


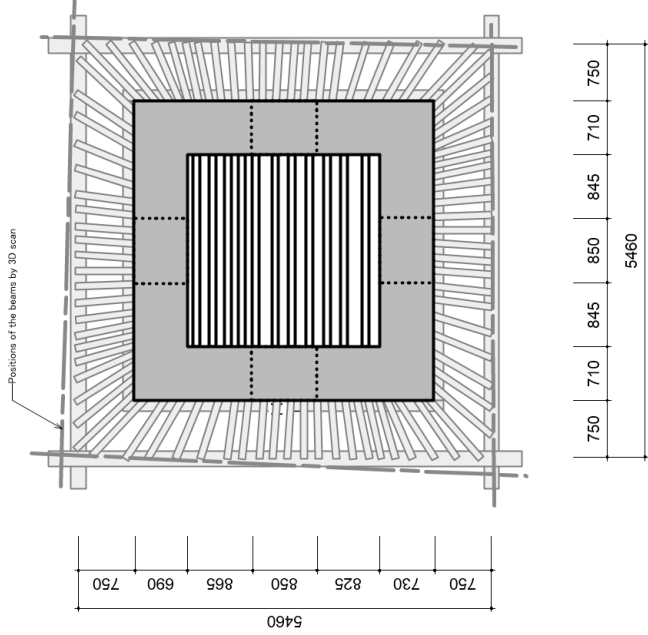
B: 2nd floor



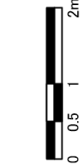
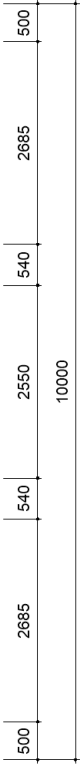
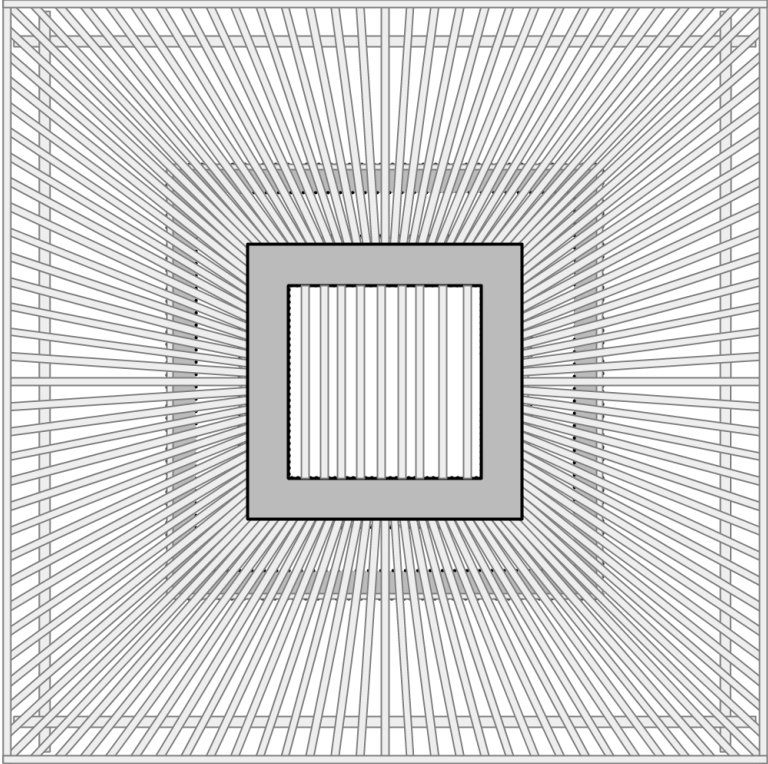
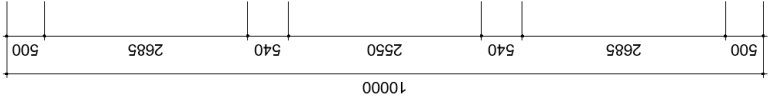
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- G01 : Floor plan of pillars and wall, 1st storey
- G02 : Plan of joists, 2nd storey
- G03 : Plan of struts and fascia boards of the 1st tier
- G04 : Plan of rafters of the 1st tier
- G05 : Plan of struts of 2nd tier and joists, 3rd storey
- G06 : Plan of struts and fascia boards of the 3rd tier
- G07 : Plan of beams between 3rd and 4th storey
- G08 : Plan of rafters of the 2nd tier
- G09 : Plan of ridge beams, 4th storey
- G10 : Plan of rafters of the 3rd tier
- G11 : North elevation
- G12 : East elevation
- G13 : West elevation
- G14 : South elevation
- G15 : Section of X (EW) direction
- G16 : Section of Y (NS) direction
- G17 : Size of bricks

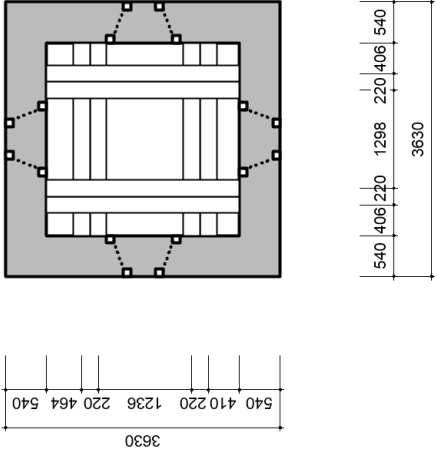




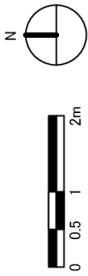
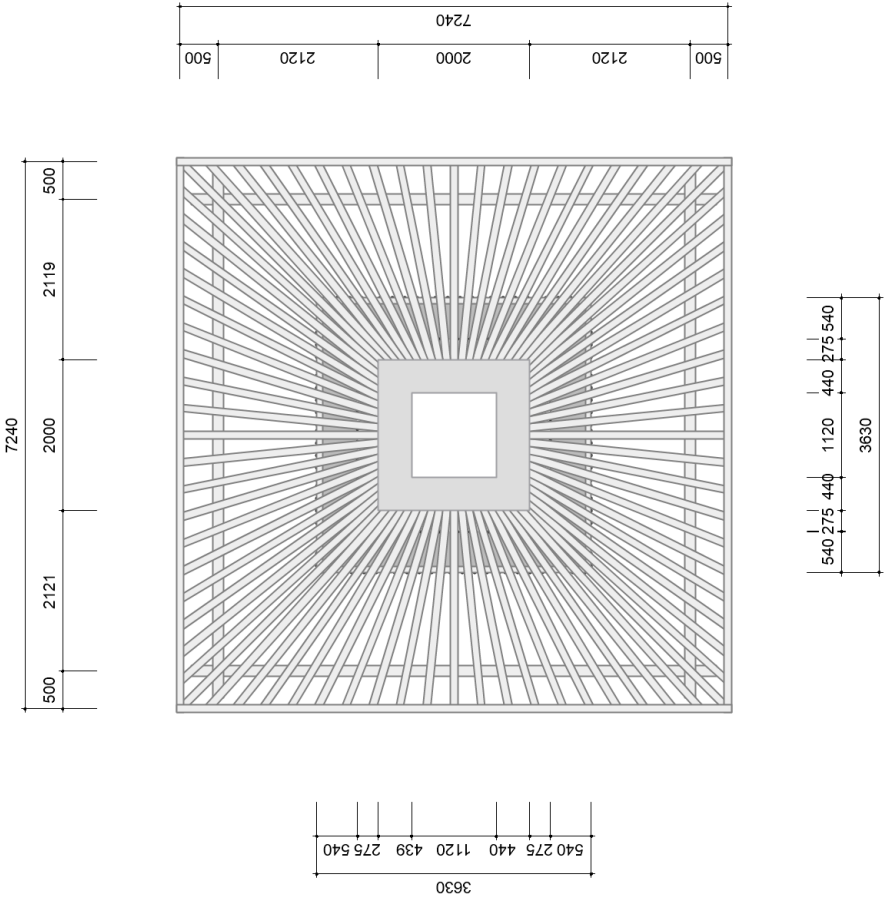
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	Drawing Title		Plan of joists, second storey		Scale		1:100 (A4)		Researcher		Koshihara lab	



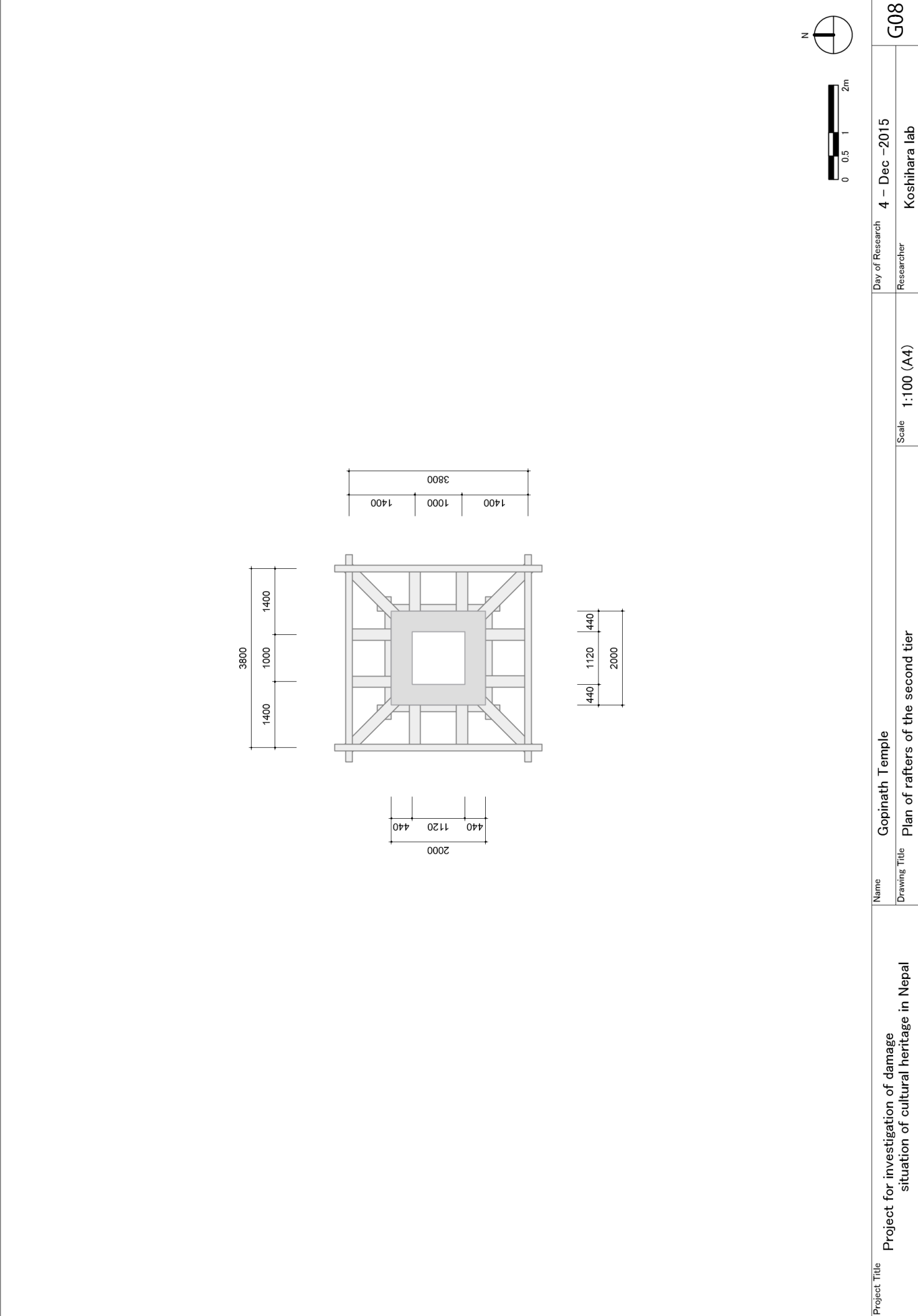
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			Drawing Title		Plan of rafters of the first tier		Researcher		Koshihara lab		
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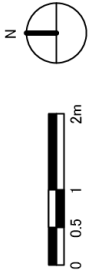
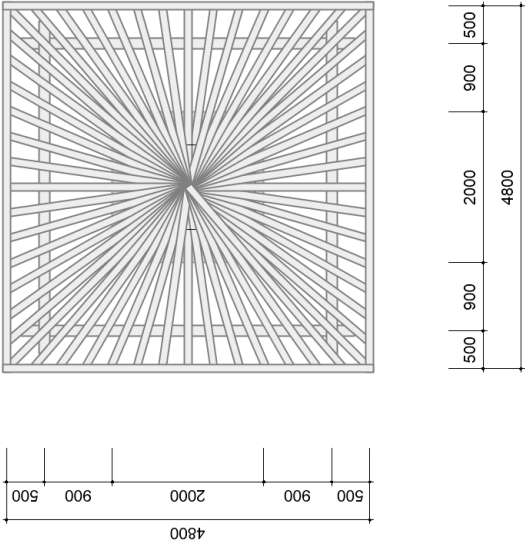


Project Title	Project for investigation of damage situation of cultural heritage in Nepal		Name		Gopinath Temple		Day of Research		4 - Dec -2015		G06	
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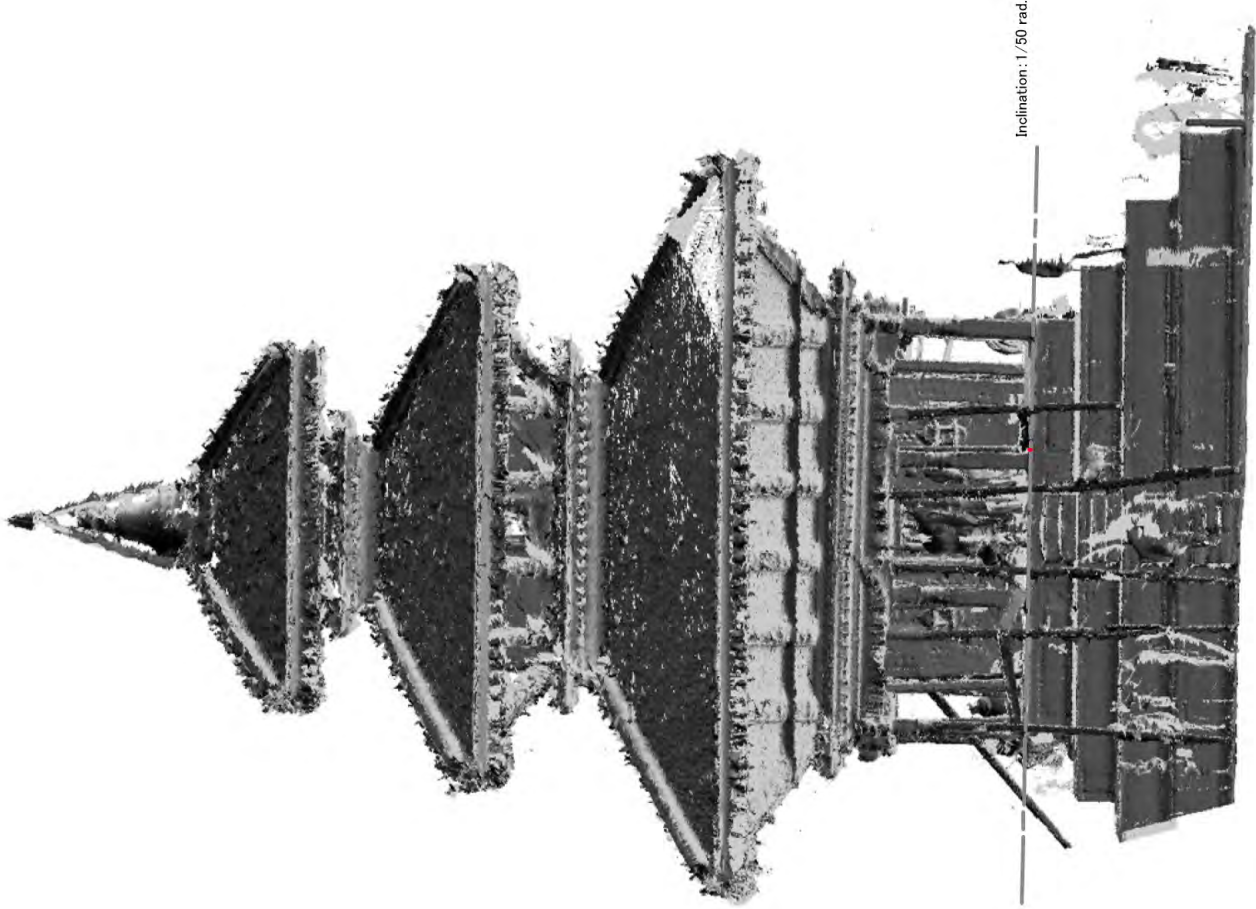


Project Title	Project for investigation of damage situation of cultural heritage in Nepal			
	Name		Gopinath Temple	
	Drawing Title		Plan of beams between third and fourth storey	
	Scale		1:100 (A4)	
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	Researcher		Koshihara lab	
G07				

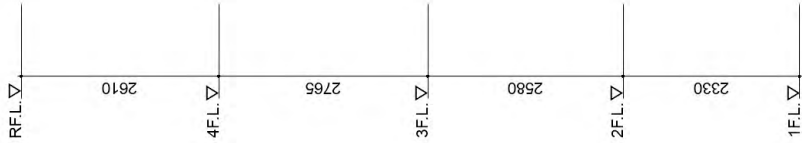




Project Title	Project for investigation of damage situation of cultural heritage in Nepal		Name	Gopinath Temple		Day of Research	4 – Dec –2015		G10	
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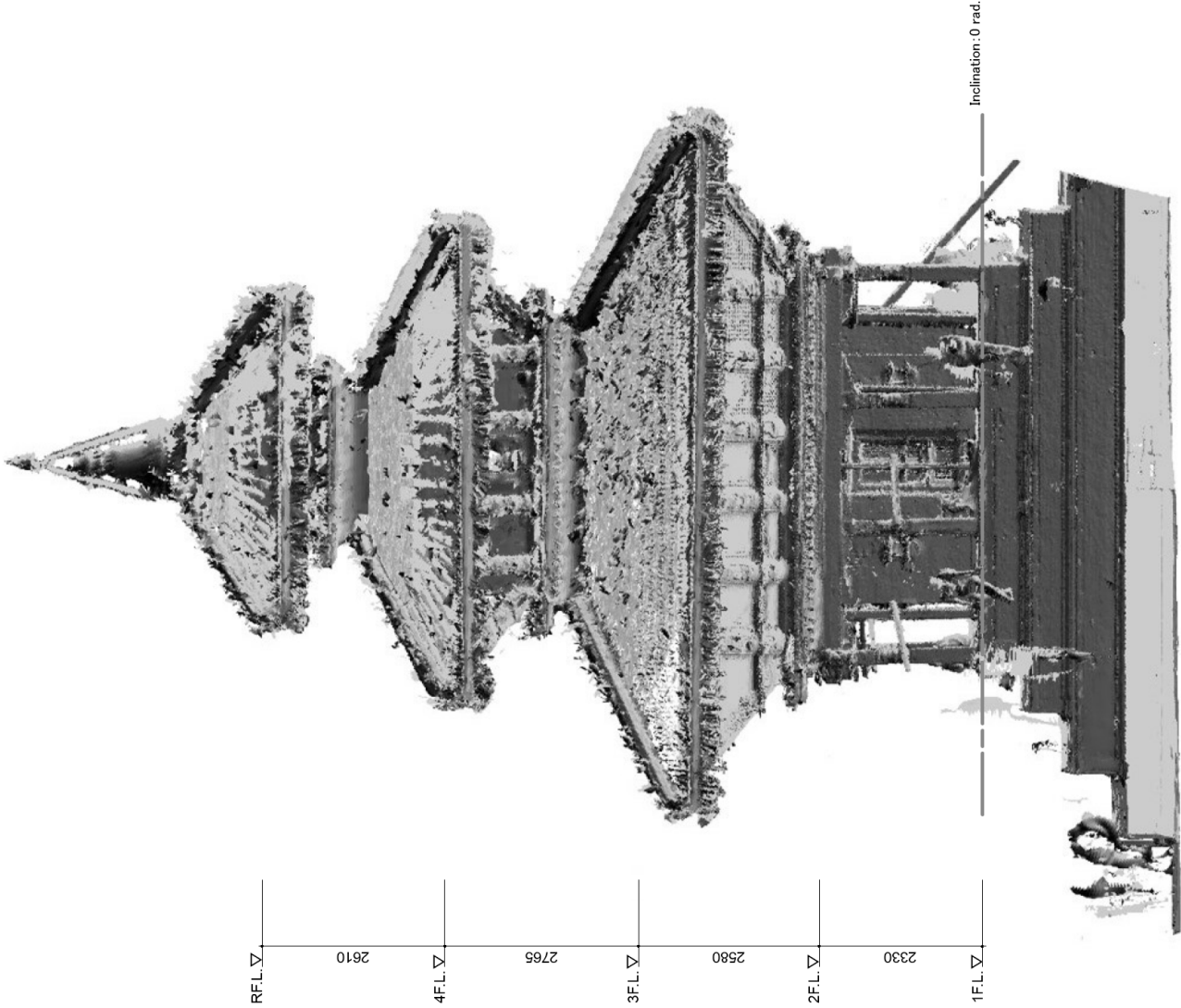


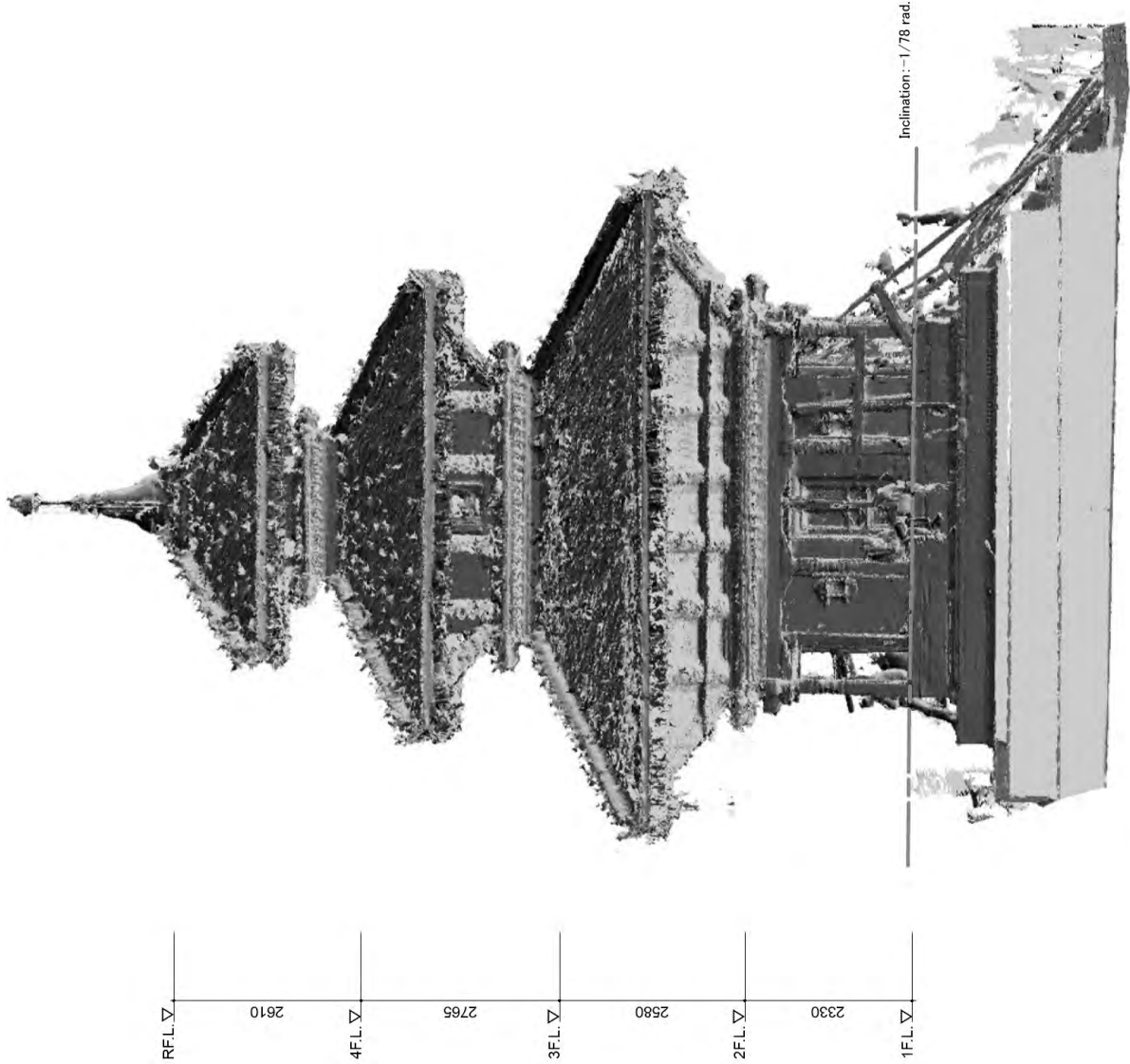
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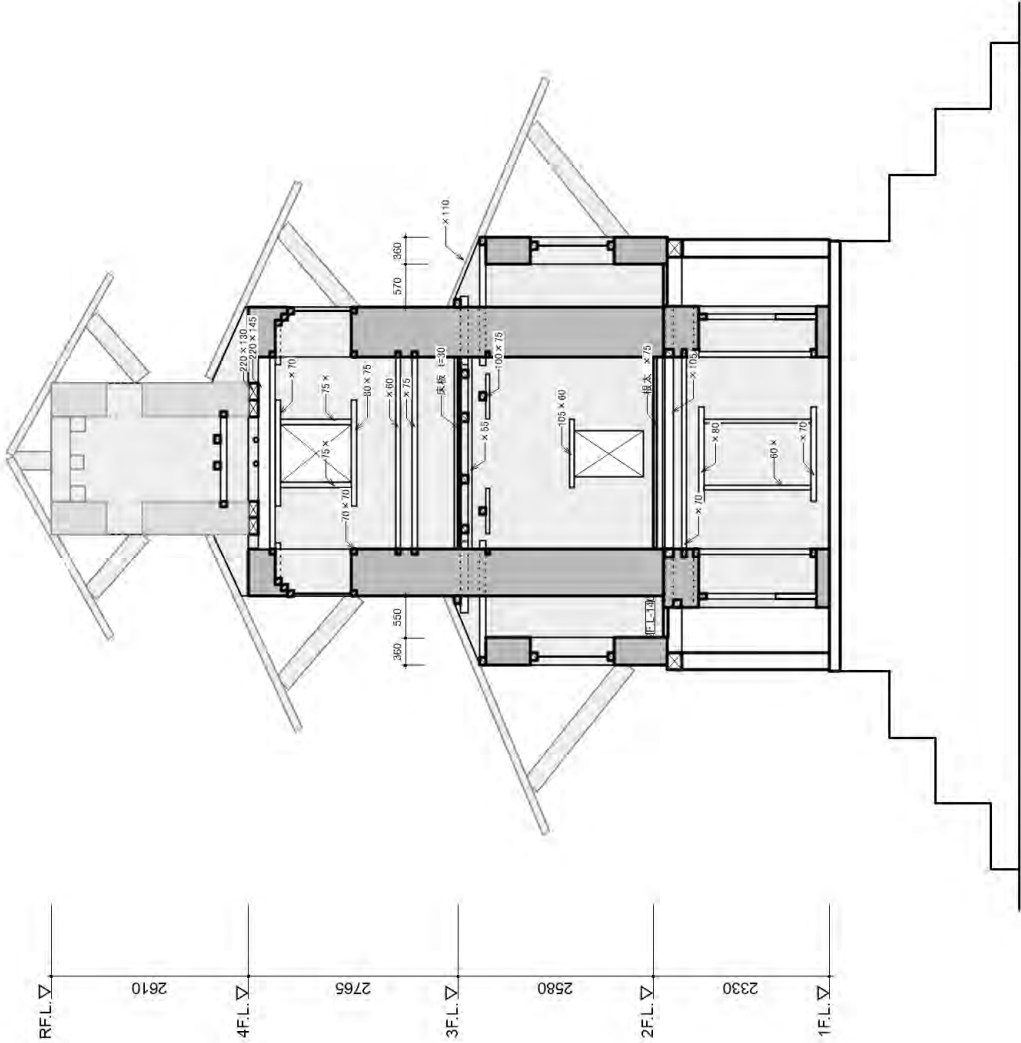
Project Title	Project for investigation of damage situation of cultural heritage in Nepal			
	Name		Gopinath Temple	
	Drawing Title		East Elevation	
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	Day of Research		4 - Dec -2015	
G12				

Scale 1:100 (A4)

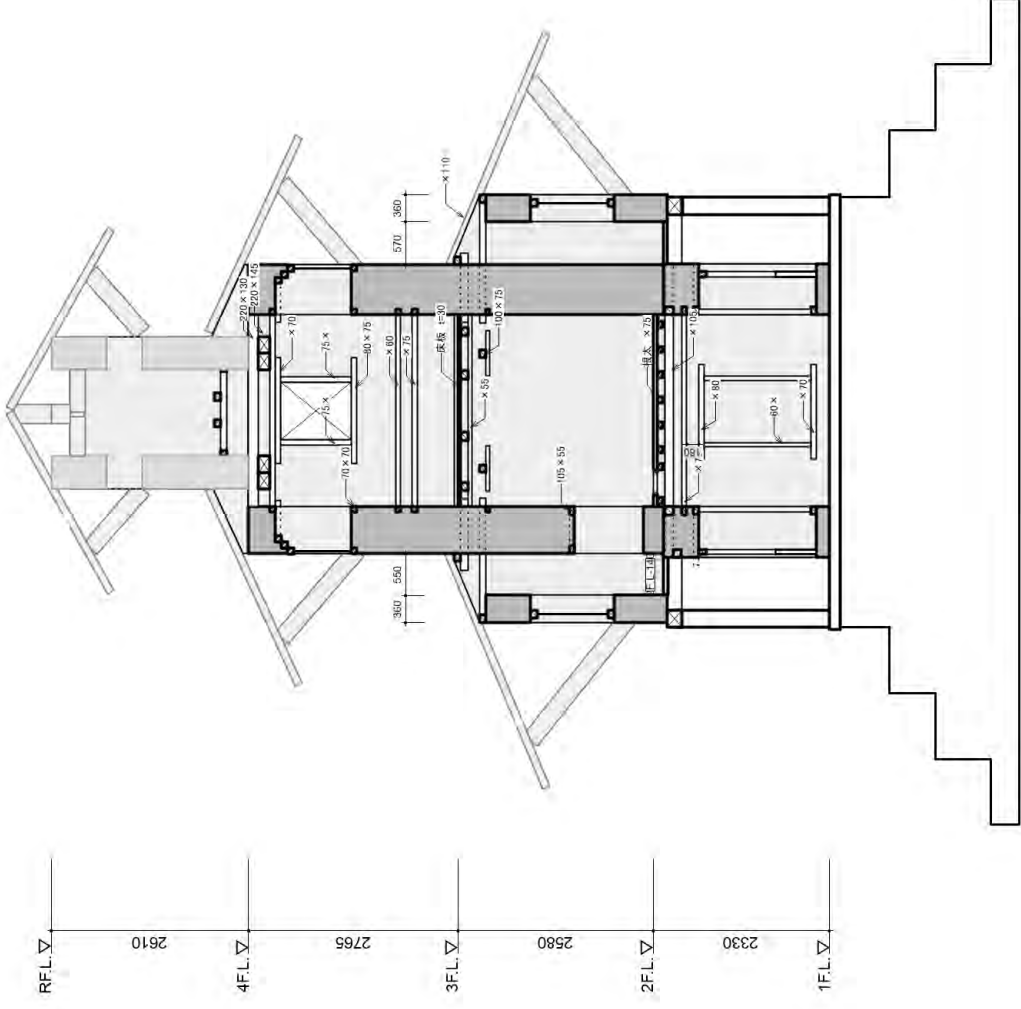




Project Title	Project for investigation of damage situation of cultural heritage in Nepal											
	Name		Gopinath Temple		Day of Research		4 - Dec -2015					
	Drawing Title		South Elevation		Scale		1:100 (A4)		Researcher		Koshihara lab	
G14												

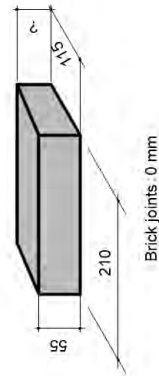


Project Title	Project for investigation of damage situation of cultural heritage in Nepal		Name		Gopinath Temple		Day of Research		4 - Dec -2015		G15	
	Drawing Title		Section-X (EW)		Scale		1:100 (A4)		Researcher		Koshihara lab	

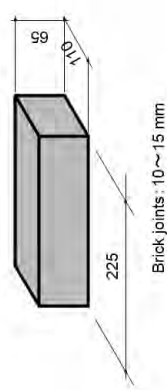


Project Title	Project for investigation of damage situation of cultural heritage in Nepal		Name		Gopinath Temple		Day of Research		4 - Dec -2015		G16	
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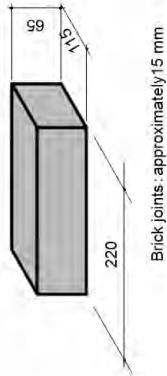
A: Outer wall of the 1st floor



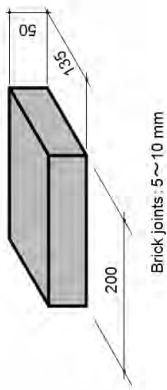
B: Inner wall of the 1st floor



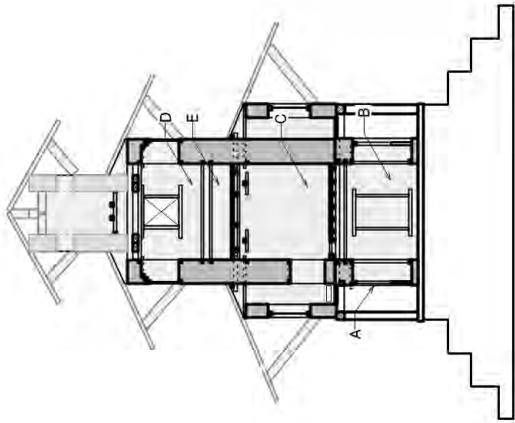
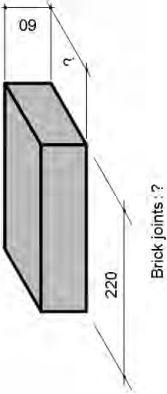
C: 2nd floor



D: 3rd floor-1



E: 3rd floor-2



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Structural Survey of Historic Buildings

2016
