Study on Compressive Performance and Safety Assessment of Stone Masonry Structure in Tibet

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Abstract. Tibetan stone masonry is different from common masonry structure. However, currently, few studies on its structural characteristics and mechanical properties are conducted. This paper summarizes the materials, composition and masonry methods of Tibetan stone masonry, and analyzes its structural characteristics. A uniaxial compression test on the small specimens built in the laboratory and the full-scale wall specimens on the site is conducted to explore the damage mechanism of the Tibetan stone masonry. Based on the compression performance of Tibetan stone masonry, this paper proposes the factor set, weight coefficient, and rating criteria of the safety assessment of the Tibetan stone masonry components by using the fuzzy comprehensive evaluation and analytic hierarchy method. The evaluation method of the safety status of components is also put forward, which is validated by the test results.

1. Introduction

There are quantities of stone masonry buildings in the Tibet Autonomous Region of China, including distinctive cultural heritage buildings, such as the Potala Palace and the Jokhang Temple, as well as modern civil buildings featuring traditional techniques. The structure of the Tibetan stone masonry building belongs to the rubble masonry structure, which has its own unique features. The present research in this field focuses mainly on its architectural style and artistic performance, but little its structural characteristics.

The identification and safety evaluation of masonry structures, especially ancient building masonry structures, has always been a research hotspot with many challenges to tackle. The safety assessment method for masonry structures proposed by domestic and foreign scholars can be divided into standard evaluation method\textsuperscript{[1]}\textsuperscript{[2]}, state evaluation method\textsuperscript{[3]}\textsuperscript{[6]}, numerical simulation evaluation method\textsuperscript{[7]}\textsuperscript{[8]}, and fuzzy comprehensive evaluation method\textsuperscript{[9]}\textsuperscript{[12]}. However, there are few studies on the safety assessment of stone masonry. A large number of cultural relics and civil buildings in Tibet were built by using traditional Tibetan stone masonry. Therefore, it is urgent to establish an evaluation criterion and assessment methods applicable to Tibetan stone masonry.

This paper first summarizes the materials, composition, and masonry methods of Tibetan stone masonry, and then analyzes its structural characteristics. A uniaxial compression test on the small specimens built in the laboratory and the full-scale wall specimens on the site is conducted to explore the damage mechanism of the Tibetan stone masonry. Based on the compression performance of Tibetan stone masonry, this paper proposes the factor set, weight coefficient, and rating criteria of the safety...
assessment of the Tibetan stone masonry components by using the fuzzy comprehensive evaluation and analytic hierarchy method. The evaluation method of the safety status of components is also put forward, which is validated by the test results.

2. Composition and structural characteristics of Tibetan stone masonry

Block stone overlying on rubble stone is a common type of Tibetan stone masonry and has a certain laws in distribution and periodicity. At the same time, it is random in shape and size just like the block stone. In addition, the Tibetan stone masonry tends to be thicker, which makes it possible to build tall walls. Those are clearly different from the common rubble masonry. A typical Tibetan stone wall is shown in Figure 1.

![Figure 1. Typical Tibetan stone masonry](image)

The materials used in Tibetan stone masonry are basically traditional materials in Tibet, such as stone and soil. The stone is mainly sturdy granite, diorite, and slate, which are usually in the form of block and sheet stone. The former is different in shape and is roughly in the shape of strip. Its weight is limited by the weight that one can carry. The latter is in the shape of a sheet, about 2 to 3 cm thick, and is mainly distributed between the layers of the stone to flatten and close the gap. It is filled with mud, which is mixed with loess and water with no strict mixing ratio. After the wall is completed, the mud solidifies in the natural environment. Compared with the common masonry mortar, the mud is less strong but more compressible. The composition of Tibetan stone masonry is shown in Figure 2.

![Figure 2. Composition of Tibetan stone masonry](image)

The Tibetan stone masonry is built layer by layer with each layer being basically horizontal. The block stone layers and sheet stone layers often take turns. The distribution of Tibetan stone masonry is between the grouted masonry and the rubble masonry. The Tibetan stone masonry also has its own unique features in the profile, which will affect the structural performance of the wall. For example, first, Tibetan stone wall is obviously thicker than the common masonry. Tall buildings such as the Potala Palace even have walls with a maximum thickness of over 5 m. Second, the thickness of the outer wall is decreased by 1/10 to 1/8 so that the building can be more stable. Thirdly, the stones used in the inner and outer walls are regular while in the middle, there are stones of different specifications or gravels, forming “filled layer”.

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Based on the masonry characteristics, the main structural features of Tibetan stone masonry are:

1. Quasi-periodic and weakly orthogonal anisotropy in the plane. The Tibetan stone masonry is layered based on the rule “rock-mud-rubble-mud...” with its in-plane structural features between stone masonry (orthotropy) and rubble masonry (close to isotropic).

2. The stones in each layer remain flat with similar heights and weight. Thick layers of mud with similar thickness are placed between the stone layers. The vertical loads from the top (including the floor load and the weight of the upper wall) are uniformly transmitted from the top to the bottom.

3. Adduction contributes to the overall stability to some extent. The wall of Tibetan stone masonry is in a right-angled trapezoidal shape, which moves down its center of gravity, thereby reducing the possibility of declining and collapsing. In addition, thinner wall at the top leads to smaller self-weight, which is also beneficial to its self-supporting.

4. Between the corner and the inner and outer stone blocks, a longer stone block is used for connecting. Combined with the mud in the gap, the Tibetan stone masonry is stronger as a whole.

3. Study on compressive performance

3.1. Laboratory compression test

Based on recommendations for the axial compression test of masonry in relevant domestic and foreign norms \[13\]-\[16\] and the test methods used by scholars at home and abroad \[17\]-\[18\], this paper uses the prismatic specimens for compression test. The design principle is to set the size of the stone and mud layer in the specimen as close as possible to that in the real situation. The granite cut by machine is selected; the block stone is in the shape of 400×200×150 mm regular hexahedron; the rubble is the 15 mm-thick sheet stone. The upper and lower surfaces of the stone are chiseled. The thickness of the mud layer tends to be masonry processed and formed by the specimen, not less than 10 mm. The mud is prepared by using the native loess of Lhasa, Tibet, with a moisture content of 15%.

Since there are few studies on Tibetan stone masonry at home and abroad, in order to find the most suitable type of specimen for this structural system, this paper builds three different specimens: three-layer specimens without vertical mortar joints, five-layer specimen with vertical mortar seam, and five-layer specimen with vertical mortar seam and sheet stone layer which are numbered FP1, FP2, FP3. FP1 is a three-layer stone specimen with two horizontal mortar joints; FP2 is a five-layer stone specimen with a vertical mortar joint in the middle; FP3 is a five-layer specimen with block stone - block stone - sheet stone - block stone with vertical seam - block stone from the bottom to the top. Among them, the five-layer specimen should consider to use the uppermost and lowermost stone and the adjacent mud layer as the constraint while the intermediate three-layer stone and two horizontal mortar-stitched masonry as the object of investigation. The photo of specimens are shown in Figure 3.

![Figure 3. The photo of specimens](image)

The compression deformation and damage development of the three different specimens were similar in the test. First, the mud layer is compressed visibly. With the increase of the load, a number of vertical cracks appear at the junction of the stone and the mortar joint and extend upward and downward. The cracks in the pieces with vertical mortar joint expand laterally. The earliest damage in the FP3 specimens for simulating the structural characteristics of the Tibetan
stone masonry is the cracking in the sheet stone; then vertical cracks appear at the interface between the stone and the mud while the vertical mortal joint also expands significantly. As the load increases, the damage of the above three forms also develops with more and wider cracks. The final destruction modes of the three kinds of specimens are vertical crack penetration, and the block stones are split into pieces. The whole specimen loses its bearing capacity due to instability and bulk damage. The damage process of the typical specimen (FP3) under pressure is shown in Figure 4. The initial cracking strength and ultimate strength of each specimen are shown in Table 1.

![Figure 4. Damages of FP3 in compressing](a) Front side (b) Back side (c) Lateral side)

### Table 1 Test results of strength and elastic modulus of stone prismatic specimens

| Number | Initial cracking strength $f_i$(MPa) | Ultimate strength $f_u$(MPa) |
|--------|-------------------------------------|----------------------------|
| FP1    | 6.25                                | >7.66*                     |
| FP2    | 5.80                                | 12.93                      |
| FP3    | 5.14                                | 11.08                      |

*Note: The ultimate strength is not reached due to equipment failure

3.2. Compression test of full-scale wall

Two test wall pieces (W1 and W2) are built using the traditional wall-building technology by Tibetan artisans with relevant experience. The dimensions (length×thickness×height) are 1.0 m×0.6 m×1.4 m and 0.9 m×0.5 m×1.4 m respectively. Adduction is not set in the test, making it closer to the low-rise residential stone wall. The masonry process of W1 and W2 is the same, but the W2 is visually more regular and compact.

The equipment used in this test are the simple reaction frame, jack, and dial gauge. The reaction frame forms a closed rigid frame with the wall directly built on its ground beam. Two thick steel plates are placed on the top of the wall, on whose top lies a load beam. The jack is placed above the load beam. During the test, the jack is lifted up, so the lifting force acts under the reaction beam and reaction beam then provides a downward reaction force applies uniform load to the top of the wall through the load beam and the steel plate. The arrangement of the test are shown in Figure 5. The test adopts graded loading with at least 5 minutes for each load for the reading of the dial gauge to be stable. Since the ultimate strength of the wall is unknown, in order to ensure safety, each wall is subjected to multiple stages of loading and unloading. The vertical deformation was collected using a dial gauge.
Figure 5. The arrangement of the test

The pressure test of the full-scale wall: firstly, the mud is compressed, meaning the mud on the surface of the wall is squeezed out and peeled off in the early stage of the force; then the local cracking of the sheet stone occurs randomly. Limited by the test conditions, the wall is not pushed to the ultimate failure state, but the test results can reflect the real compression performance, thus obtaining the elastic modulus reference value. The vertical force-deformation curve of the wall is obtained in the on-site compression test, as shown in Figure 6.

Figure 6. Vertical load-displacement curve of walls

Divide the relative displacement (ie, the amount of compression) by the total height of the wall to obtain the average compressive strain; divide the pressure value by the cross-sectional area of the wall to obtain the average compressive stress. Conduct staged linear numerical fitting of the experimental data. The slope of the straight line is regarded as the linear growth rate of the stress at the stage relative to the strain, which is the elasticity modulus $E$ obtained in each loading process. The results are shown in Table 2.

| Loading process (1) | (2) | (3) | (4) |
|---------------------|-----|-----|-----|
| W1                  | 18.34 | 17.60 | 25.28 | -   |
| W2                  | 66.29 | 81.15 | 108.15 | 263.10 |

It can be seen from the results that the elastic modulus of the two test walls are 17.60 mpa-25.28 MPa and 66.29-263.10 MPa respectively (the elastic modulus of W1 is less than that of W2), which are far lower than the value (2250-7300MPa) for the elastic modulus of rough stone masonry specified in Code for Design of Masonry Structures (GB 50003-2011) [19]. The reason is that the deformation of the wall is mainly provided by the mud, and the Tibetan stone masonry contains much mud with high compressibility, thus stronger deformation capacity and lower elastic modulus. The elastic modulus of the test wall shows a trend of increase in the process of multiple loading. That is due to the fact that the wall is compacted while the mud is compressed in loading. The results of the two test walls are also quite different, which is because the masonry of the stone wall in Tibet is quite random, and the thickness and uniformity of the mud of the two walls are quite different.
4. Study on structural safety assessment

4.1. Introduction of fuzzy comprehensive research method

Fuzzy comprehensive evaluation method \(^9\) draw lessons from the principle of binary contrast of the sorting method, and indirectly determine the weight of each factor through judgment matrix for the comparison of two factors. The steps are as follows:

Firstly, the hierarchical structure is established based on the factors involved in the problem and their relations.

Secondly, the influence degree of each factor at the same level on the previous level is compared in pairs. The judgment matrix \(A\) is constructed by using the proportional scale assignment. In order to avoid logic errors, the consistency test is required to determine the maximum (absolute value) eigenvalue \(\lambda_{\text{max}}\) of the judgment matrix \(A\) for consistency check.

Thirdly, obtain and normalize the eigenvector \(W\) corresponding to the maximum (absolute value) eigenvalue \(\lambda_{\text{max}}\) of the judgment matrix \(A\). The obtained eigenvector is the influence weight value of each factor at this level relative to a certain factor at the previous level.

Fourthly, construct the membership vector \(R\) of each factor in the layer, and obtain the evaluation grade vector \(X\) by calculating the eigenvector \(W\) and the membership vector \(R\). The grade corresponding to the maximum value is the evaluation result.

4.2. Factor collection and weight coefficient for safety assessment of Tibetan stone masonry components

Axial compression test shows the compression failure mechanism of Tibetan stone masonry: the mud expands laterally under pressure, exerting surface tension on the stone. Combined with stress concentration and bending stress, the stone suffers uneven complex stress. When the tensile stress is stronger than that of the stone, the stone cracks, and sheet stones usually crack earlier than block stone. The gap left between stones is equal to the stone crack. Under the continuous pressure load, the gap or crack will expand laterally, upward, and downward; eventually the stone cracks into multiple short columns and become unstable. Therefore, crack is an important factor for evaluating the state of Tibetan stone wall components. Test result shows that cracking of a single stone might be an incident and has a small impact on the overall stress state. When the cracks extend up and down in more than a stone layer, they are mainly caused by stress. The referential meaning of crack pattern can be quantified and graded by referring to indexes in Standard for dangerous building appraisal (JGJ 125-2016) \(^1\) and Standard for appraisal of reliability of civil buildings (GB50292-2015) \(^2\).

Another factor in the evaluation of Tibetan masonry components is deformation, which includes side bending deformation and the overall tilt of the wall. The existing research object is a single wall, while the influence of wall deformation has not been studied in detail. Therefore, indexes in Standard for dangerous building appraisal (JGJ 125-2016) \(^1\) and Standard for appraisal of reliability of civil buildings (GB50292-2015) \(^2\) can be used for reference for quantification and grading for improvement.

The suggested third factor for evaluating of Tibetan masonry components is the material state, which is because that Tibetan masonry uses mud to bond, which is special. The stone itself is likely to degrade, which should be paid attention to.

In conclusion, it is suggested to take crack, deformation and material state as three factors for safety assessment of Tibetan stone masonry components by taking full consideration of its characteristics and mechanism of damage under pressure. It takes the three main factors of stress, deformation, and material are taken into account and determine their weight based on the basic principle of analytic hierarchy process (AHP). then, scale assignment is used after pairwise comparison and the judgment matrix is built. The weight analysis is shown in table 3, which has passed the consistency.
Table 3 weight analysis of evaluation factors

|                | Crack | Deformation | Material state | Weight | CR=0.0624 |<0.1 | Meet the consistency demand |
|----------------|-------|-------------|----------------|--------|-----------|-----|-----------------------------|
| Crack          | 1     | 1/3         | 5              | 0.28   |           |     |                             |
| Deformation    | 3     | 1           | 7              | 0.65   |           |     |                             |
| Material state | 1/5   | 1/7         | 1              | 0.07   |           |     |                             |

The value in the table reflects the importance ratio of the first factor compared with the second one. $1/9$, $1/7$, $1/5$, $1/3$, $1$, $3$, $5$, $7$ and $9$ respectively represent absolutely weak, very weak, weak, slightly weak, same, slightly strong, strong, very strong and absolutely strong with the median value can be taken.

The judgment matrix obtained is:

$$ A = \begin{bmatrix} 1 & 1/3 & 5 \\ 3 & 1 & 7 \\ 1/5 & 1/7 & 1 \end{bmatrix} $$

The maximum (absolute value) eigenvalue $\lambda_{\text{max}}$ of the judgment matrix $A$ and the corresponding eigenvector $W$ are:

$$ \lambda_{\text{max}}=3.0649, \quad W=[0.28 \ 0.65 \ 0.07]^T $$

After determining the evaluation factors, it is necessary to establish a factor grading criteria. In order to facilitate the application and act in line with the existing standards and general evaluation methods, it is recommended to adopt four safety grades $a, b, c, d$, whose referential meaning corresponds to the Standard for appraisal of reliability of civil buildings (GB50292-2015) \[2\]. The grade of cracks is determined based on the compressive damage mechanism of Tibetan masonry, and Standard for dangerous building appraisal (JGJ 125-2016) \[1\] is partially adopted to put forward the proposed quantitative indexes. By comprehensively adopting relevant provisions of Standard for dangerous building appraisal (JGJ 125-2016) \[1\] and Standard for appraisal of reliability of civil buildings (GB50292-2015) \[2\], considering the characteristics of Tibetan masonry materials and structures, the evaluation indexes for deformation and material status are proposed. The grading criteria for each factor are shown in table 4.

Table 4 standard for state evaluation of Tibetan masonry components

| Grade | Crack | Deformation | Material state | Implications and countermeasures |
|-------|-------|-------------|----------------|---------------------------------|
| $a$   | No stone cracking or significant cracks between stones | No obvious overall or local deformation of stone wall | No weathering, pulverization, corrosion; bonding material shows no sign of performance degradation | Meet the requirements of grade $a$; has enough bearing capacity; no need to be dealt with |
| $b$   | Occasional stone cracking; no extension the upper and lower layers | A medial displacement of the structure plane over 1/350 and no more than 1/300 times the height of the component | No weathering, pulverization, and corrosion; masonry quality of the bonding materials is average, or shows the signs of weathering, pulverization, and loosing | Slightly lower than level $a$; not significantly affect the bearing capacity; it is acceptable not to be dealt with |
The upper and lower extension length of cracks exceeds the height of one layer of stones, but no more than the height of 1/3 of the masonry component

Weathering, peeling, pulverization of bonding materials; damp and moldy on the surface; effective cross section is weakened by less than 15%

Fail to meet grade a requirements; significantly affect the carrying capacity; shall be dealt with

A medial displacement of the structure plane over 1/300 and no more than 1/150 of the height of the component

A large area of weathering, peeling, pulverization of bonding materials, damp and moldy, etc.; the effective cross section is weakened by more than 15%

Serious impact carrying capacity; must be dealt with immediately or timely

| c | Multiple cracks over 1/3 height of masonry component or cracks over 1/2 height of masonry component |
|---|---------------------------------------------------------------|
| d | A medial displacement of the structural plane that exceeds the height of 1/300 and 1/150 times of the component; or the partial inclined deformation of the wall relative to the whole building is greater than 7‰; or the joint of adjacent members is broken into a continuous seam |

4.3. Case analysis

The evaluation method is applied to the prismatic sample FP3 and full-scale W1 after loading and unloading.

The judgment matrix is:

\[
A = \begin{bmatrix}
1 & 1/3 & 5 \\
3 & 1 & 7 \\
1/5 & 1/7 & 1
\end{bmatrix}
\]

The eigenvector W representing the weight of crack, deformation, and material state is:

\[
W = [0.28 \ 0.65 \ 0.07]^T
\]

Take Table 4 as the evaluation standard of each factor, the damage and quantity of the two specimens are recorded by means of inspection and detection. Their respective evaluation matrices are determined by means of proportional distribution and qualitative judgment of state. The evaluation matrices of FP2 and W1 specimens are:

\[
R_{FP3} = \begin{bmatrix}
0 & 0.3 & 0.7 & 0 \\
0 & 1 & 0 & 0 \\
0 & 1 & 0 & 0
\end{bmatrix}; \quad R_{W1} = \begin{bmatrix}
0 & 0.8 & 0.2 & 0 \\
0 & 1 & 0 & 0 \\
0 & 1 & 0 & 0
\end{bmatrix}
\]

The following equations can be obtained:

\[
X_{FP3} = W^T \cdot R_{FP3} = [0.28 \ 0.65 \ 0.07] \begin{bmatrix}
0 & 0.3 & 0.7 & 0 \\
0 & 0 & 0 & 1 \\
0 & 1 & 0 & 0
\end{bmatrix} = [0 \ 0.1556 \ 0.1953 \ 0.6491]
\]

\[
X_{W1} = W^T \cdot R_{W1} = [0.28 \ 0.65 \ 0.07] \begin{bmatrix}
0 & 0.8 & 0.2 & 0 \\
0 & 1 & 0 & 0 \\
0 & 1 & 0 & 0
\end{bmatrix} = [0 \ 0.9442 \ 0.0558 \ 0]
\]
The maximum value of the rating vector of FP3 is in grade $d$, which indicates that the state of the specimen is grade $d$, an obvious dangerous state. The evaluation result is consistent with the test result. At this time, the specimen has reached the limit state, the load displacement curve enters the flat section, the maximum pressure value fails to increase, and the specimen is on the verge of falling into pieces after unloading.

The maximum value of the rating vector of $W1$ falls into grade $b$, indicating that the specimen state is grade $b$. Despite a certain local rock cracks, the wall remains largely in the linear elastic stage from the experiment and the load displacement curve. Therefore, the evaluation result is: the existing damage does not significantly affect the bearing capacity and it is acceptable not to handle it.

It can be seen from the above cases that the fuzzy comprehensive evaluation method is simple and feasible to evaluate the safety state of Tibetan masonry components. At the same time, the intuitive experience is transformed into the comprehensive evaluation based on mathematical model, making the evaluation result corresponding with the test result. This method is suitable for safety evaluation at the component level. In actual detection and appraisal, it is feasible to act in line with the current appraisal standards after completing the safety evaluation of all components so as to conduct staged comprehensive evaluation of the buildings by determining the proportion of dangerous components.

5. Conclusion
(1) Compared with common rubble masonry, Tibetan masonry has its unique structural features, which will significantly affect the structural performance of the wall. The features include: quasi-periodic characteristic and weak orthogonal anisotropy in plane; flat layer, which is beneficial to structure stress because of uniform loading; thicker at the bottom and thinner at the top, which is beneficial to the overall stability; bonding of the raft and the mud makes it better as a whole.

(2) During axial compression, mud is compressed first, followed by local and random cracking of stone, which is mainly caused by complex stress state, among which tensile stress and bending stress are non-negligible factors. When the through crack is formed, the Tibetan stone masonry quickly enters the stage of failure and is finally divided into multiple short columns. The masonry is unstable and falls into pieces, losing its bearing capacity. The elastic modulus of Tibetan masonry is obviously smaller than that of common masonry.

(3) The factor set for safety assessment of Tibetan masonry components can be set to include crack, deformation, and material state. The weight of the three factors can be calculated by pair comparison, scale assignment while fuzzy comprehensive evaluation method can be used for the safety assessment of each component.

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