Investigation of fuzzily arranged "Hanegi" in traditional wooden building
Kataoka, Y.1  Itoh, H.2  Inoue, S.3

ABSTRACT
The purpose of my investigation is to clarify the mechanical characteristics of fuzzily arranged Hanegi (Photo 3) of Japanese traditional buildings, and to give suggestions as to possibility of application to structural design of modern wooden buildings. Hanegi is an unstable structural system of roof frame which is supported with the action of levers. The writers analyze why an unstable structural system was invented in old time and why the construction method was inherited till modern age. Firstly, I introduce two kinds of devices which are supported by the action with eaves and of which mechanical characteristics is similar to Hanegi. And then, we discuss the behavior of Hanegi which is subjected to snow load and wind load, and the reasons of the fuzzy and unstable cantilever system have been applied to roof structures. After that, the authors suggest that the transmission of a epoch-making technique has not always been rightfully handed down to after age, by taking a roof destruction as an example. Lastly, an example of new traditional building will be introduced, of which roof structure are supported by Hanegi and it was recently completed in Kyoto of Japan.

INTRODUCTION
The roof construction method, "Hanegi", was invented in the 1500's in Japan. Since then, Hanegi has been used to build roof structure of big wooden buildings such as Buddhist temples, shrines or others. Hanegi constitutes a characteristic feature of big roof and deep eaves of Japanese wooden buildings. Japanese summer is high temperature, and it shows a high percentage of humidity. It is necessary to lengthen the eaves to protect the building from the rottenness of wood which is exposed to wind and rain, and to interrupt sunlight of summer to keep an indoor residence environment favorably. These are the reasons why the big roof and the long eaves became one of the distinctive features of the traditional wooden buildings. And Hanegi has been a very important structural element to support the long eaves.

At first, the authors introduce two kinds of traditional cantilever device, "Sohz" and a filter press, as shown in Photo 1. The former is a furniture which is made of bamboo in the garden, and the latter is a filter press of a undiluted sugar solution. They have the same mechanical characteristics as "Hanegi".

Next, some examples of Hanegi will be shown, and the writers discuss the details of the construction method of Hanegi. "Hanegi" is a unstable cantilever system of roof construction of Japanese traditional architecture. They are fuzzily arranged along the eaves and are supported on a fulcrum by utilizing the principles of the lever and fulcrum. The writer paid attention to this fuzzy and unstable cantilever system which have been applied to Hanegi.

When a building is being built, it makes it easy to adjusts the level of the height of the eaves by slope adjustment of Hanegi. And, Irregular snow load and wind load acts on the eaves, and these loads are greater than other place and are not uniform. But Hanegi equally supports them. Furthermore, when the level of the structure of the roof becomes irregular due to a change in sutra age of the building, Hanegi simplifies the re-adjustment of the level without dismantling of the roof structure. This has an important meaning for the historically important buildings. The writers discuss the structural characteristics and the details of Hanegi which became clear from the results of our recent investigations. And the basis which Hanegi has been used for, will be made clear from the dynamic viewpoint. An example of the eaves of Temple which was collapsed by snow load, is introduced, and the cause of the collapse will be discussed.

Lastly, I will show the example of a traditional wooden building which was recently designed. Roof load of the building is supported only by Hanegis which were fuzzily arranged along the eaves.

1 Professor, Dept. of Architecture, Chubu University, 1200 Matsumoto Aichi Japan
2 Professor Emeritus, Chubu University, Itoh Heizaemon Design Office, 202 Murata, Wakamatsu Tokyo Japan
3 Architect, Itoh Heizaemon Design Office, 202 Murata, Wakamatsu Shinjuku Tokyo Japan
"SOHZ" IN A GARDEN AND FILTER PRESS OF SUGAR SOLUTION

"Sohzu" is shown in Photo 1. Sohz, in other word Sisiodosi, is a furniture which is made of bamboo, and it is set in old Japanese garden. The head of bamboo is cut with an acute angle and it is supported on the frame. As the opposite side is longer and heavier than the head, the bottom is set on the stone. A drop of water continuously falls into a hole of the head. When the space between the head and a node of bamboo is filled with water, the head weight just keeps in equilibrium with the bottom. After that, head becomes heavier than the other side, and the bottom part from the stone, and bamboo inclines. Water runs out, and the next moment unbalanced bamboo rotates conversely with rapidity, and the bottom of the bamboo hits the stone with a airy sound. The rotation is repeated regularly on one occasion and irregularly on another occasion. The airy bamboo sound rings throughout the garden, and Japanese find their mind at peace to listen to the sound of the most simple furniture at fuzzy interval. This instrument is also called "Sisiodosi", because the sound drives a wild boar away who comes to eat the greens.

Sohz automatically responds to the various fuzzy conditions such as the wind, the quantity of water stream or others.

Photo 1 "Sohz" in a Garden and Filter Press

Photo 2 Fulcrum and Counter Weight of Filer Press

An unstable furniture which utilizes the principles of the lever and fulcrum, makes it possible to control the fuzzy conditions. A traditional device to clean unpolished rice, was an application of Sohz which harnesses a stream of water and water wheel.

As an other example, another application of the principles of the lever and fulcrum is a filter press to refine sugar and it is shown in Photo 1. The main element is a beam which utilizes the principles of the lever and fulcrum. As an undiluted solution contains impurities of sugar cane, it is compressed by the fulcrum to pass the liquid through a filter. Then, it is
necessary to press continuously by strong compression, and to pass it by insensible degrees through a filter for many hours to get a good liquid. The filter press should follow the displacement in accordance with a fuzzy decrease of the undiluted contains. This device should be unstable. This is a kind of follow-up control device. To satisfy these fuzzy conditions, the device which utilized the action of levers is invented. Big stones are swung from the end of the lever as shown in Photo 2. The weight is not always exact, because the consistency of an undiluted solution is not constant on each processes. A device that has fuzzy mechanism, has good performance to control the fuzzy conditions by angle of the lever and the weight of the stone. The process of press and filtration is repeated some times till it has high purity. "Wasanbon" is made from by using the filter press, and it is the most high grade sweet in Japan. A similar device has been also applied to filter press in a brewhouse of Sake, Japanese rice wine. These devices which have been worked out on the basis of the action of levers, exerted a great influence on earlier traditional construction method.

HANEGI AND ROOF FRAMING OF TRADITIONAL BUILDING

There are two kinds of beam in the roof structure of traditional buildings. One of them is a inclined beam called "Noboribari", and the other is Hanegi (Photo 3). Noboribari is supported at severl positions by other girder or short posts. So, it is a statically indeterminate beam. On the other hand, Hanegi is supported only by a fulcrum. After the main frame of roof is constructed, Hanegi is inserted into the roof frame, and it is put on a fulcrum. The length of the inner part from the fulcrum is two or three times of the length of the head. The bottom is supported by temporary element as shown in Photo 4, because it is out of balance. As the result, it is an unstable supporting system of eaves. Further more, they are not arranged at stated intervals. Why does these unstable beams with fuzzy arrangement have been applied to the roof structure? The main reason is that this construction method make it possible to adapt the Hanegi to various fuzzy conditions of roof. That is to say, the various fuzzy conditions are,
1. applied loads such as typhoon or snowfall which are not constant,
2. level adjustment of the edge of the eaves under construction,
3. and exchange of the decaying parts of members of roof.

Wind load or snow load of eaves is greater than other part of roof, and the magnitude of the pressure is not same in each place. So, applied load at the head of Hanegi is big, and it is not constant. The beam which is subjected to the larger load, ought to deflect greater than adjoining beams. But the additional load is shared by the elemnt which crosses at right angle. If the deflection of the adjusting beams becomes greater than the beam after next, the load is shared to the beam again. As far as the weight of the inner part of Hanegi from supporting point is greater than the total weight of the head and the applied load, they will be well balanced.

But, if such over load as a typhoon or a snowfall is applied to the head, a Hanegi is out of balance, and it slightly rotates. Because it can support no longer any load increment. The load increment transfers to the adjoining beams. But, if there is no enough room to support it, they also rotate. The load transfers are automatically repeated to make even the each deflections until the deflections coincide with the same value.

Wind load is not constant pressure but a kind of cyclic load. The fuzzy deflection due to the over load recovers original
position periodically. Unstable and unbalanced Hanegi does not cause the destruction of the eaves. Partial unstable condition switches over to another equilibrium condition. People in a district where is visited by a severe typhoon, sometimes says that eaves waves as if it were a small surge by strong wind.

It is generally known that a scale of Hanegi in a snow country is large, and it has a big cross section. The reason is that snow load is far over the dead load, and the magnitude of snow load is about three or four times of the dead load. If the bending moment by snow load exceeds the total counter moment of Hanegis, these Hanegis rotate, and snow slips down the roof. It causes a chain reaction of snow slips, and almost snow near the area subjected to over load, is cleared away of itself. As a result, a part of roof is broken by the rotation of Hanegi. But whole destruction of roof does not occur. Irregular shape in size and irregular arrangement of Hanegi against the fuzzy action of load, would avoid the whole collapse of the roof.

![Photo 4 Various Counterbalances of Bottom of "Hanegi"

On the other hand, there are many historical buildings of which the bottom of Hanegi is fixed by some structural elements. If it is supported by slender member, it allows a rotation of Hanegi which is subjected to the over load. But, if it is fixed by some structural members as Noboribari, Hanegi should resist against the increasing fuzzy load by itself. If bending moment by applied load exceeds the ultimate bending strength, it is broken at supporting point. The next moment, all of the load is transferred to the adjoining Hanegis. But, there is no room to support all of the load, and they are also broken in the same instant. This destruction occurs continuously along the eaves. Whole collapse of eaves by heavy snow load would occur like that, and it would happen in a moment. The example of this destruction will be discussed in next section.

Fig.1 shows the arrangement of Hanegi of roof structure of Shidodera-temple. This temple is important cultural property, and Shidodera-temple was erected in 1343. The arrangement of Hanegi was investigated when the Temple had been dismantled to repair the building. Hanegi is independent to other structural members of roof frame. They are irregular in size of length and thick. And they were irregularly arranged in plane and in three dimensions. The roof of traditional
buildings nis curved and the curvature of eaves is largest. The curvature of eaves brings about elegant and beautiful shape of roof, and it is a special distinguish of the traditional buildings. Hanegi makes it possible to create the large curvature. Roof of all historical buildings can not have a large and beautiful curvature without invention of Hanegi. Hanegi is in a fair way to become rational system, and it is not important to arrange Hanegi accurately. The arrangement of other structural members and the joint of traditional buildings are complex and accurate. But an arrangement of Hanegi is only vague and fuzzy with one exception.

**DESTRUCTION OF HANEGI OF A TEMPLE IN AN AREA OF HIGH SNOWFALL**

There was a very heavy snowfall in the areas facing the Sea of Japan in 1963, and many buildings, not only the wooden buildings but also reinforced concrete buildings or steel structures, were destroyed by the snow load. The eaves of a temple of in Fukui pref. of north Japan was also destroyed by the heavy snowfall. Photo 5 shows a part of Eiheiji which is a head temple of the Zen sect. There are many temples, and Hatto is the main temple which is the biggest one in Eiheiji. The roof was destroyed by the snowfall in midnight of winter. The snow laid 2.5 meters deep on the roof in one night. The weight is about 5kN/m², and total load became about 7kN/m². The eaves of the roof is supported by Hanegi, and the total load was over the capacity of it.

The average diameter of Hanegi is about 30cm and they were arranged at intervals of 2.0m-2.5m. The length of them was about 7.5m. The diameter and the length of Hanegi at the corner of the eaves is longer than it.

The weight of which this Hanegi can keep in equilibrium with the roof load, is about 2kN/m². A self weight of Hanegi can not keep in equilibrium with the total load. So, the inner end of Hanegi was bound to other beam or posts. In this case, each beam supports independently the applied load. When the load overpasses its ultimate strength, it will be broken at a fulcrum. The moment it was broken, the load transfers to the beams of either side of it, and they are also broken in a moment. The continuous breakdowns would have happened in a short time.

If the inner end of the beam were not bound to other beam or posts, it become out of balance against snow load, and it rotates as aforementioned Sohz. The slope of the roof becomes steep, and snows would slip down and it would cause a chain reaction of snow slips. Damage of the roof would be restricted within a part of roof, and whole destruction of the roof would not have been caused.

Photo 6 shows a snapped portion of the beam and there are a mortice to connect the post and a rotted part in it. Eaves and the structural elements are easy to go bad because of leaking of rain through roof. In addition to it, as stress concentration is produced by a mortise, bending strength of the portion at a fulcrum would have been smaller than other part of beam.

After the destruction of eaves, new Hanegis were inserted into the roof frame, and they were set between all the broken Hanegis. Since then, thirty three years have run their course. Though the eaves had been repaired as it was before, it was clarified from a detailed calculation by Itoh that the Hanegi has not have enough strength to resist against the tremendous snow. In addition to this problem, there were many structural members which were subjected to a secular change. Then,
the roof was made thorough repairs last year. Photo 7 shows reinforced Hanegi of eaves under construction. The part of Hanegi near fulcrum which is subjected big bending moment was stiffened with a new couple of beams.

APPLICATION OF HANEGI TO MAIN GATE OF "HIGASHIYAMA JOHEN"

Higashiyama Johen is a mausoleum of Higashi Honganji Temple, and it situated in east side of Kyoto in Japan. The main gate was designed by Ito H. and Inoue S., and the structure was dynamically analyzed by Kataoka. Y. last year. The main structural members of roof frame are Hanegi, and the eaves was supported by it. Photo 8 shows a eaves and an arrangement of Hanegi in a center of the roof. This traditional wooden building was completed this year.

Double rafters which are hung by Hanegi, are shown in Photo 8. The rotational moment of the head of Hanegi is smaller than the counter moment of inner part of Hanegi before tiles are laid on the roof. So, the bottom of Hanegi is supported by the bar fixed on a beam. The level of height of eaves is adjusted by the compression bar. When tiles are laid on the roof, the rotational moment becomes greater than the counter moment. The ratio of rotational moment to counter moment goes up eleven percent. Stress of the bar changes to tension. To-Kyo(supporting system of top of column shown in Photo 8) is fabricated by assembling many levers and bases, and it is subjected to the compression stress perpendicular to fiber direction of the lever. So, the deflection of the eaves affect the accuracy of the level of the eaves. Ceramic tiles were laid on the roof after the construction of the roof frame had been done. The weight of tiles per square meter is about three times of the roof frame. Adjustment of the level of the eaves should be done again. Then, unstable Hanegi will be able to correspond to the adjustment of the deflection by the weight of tiles with perfect freedom.
CONCLUSION

Unstable roof construction method with Hanegi is unique and one of the most important structural characteristics of traditional wooden architecture. Though the structure is in a state of equilibration, it is an unstable structure mechanically.

This instability can control the changeable force and it leads the structure to another equilibrium condition. This structural method is based on a kind of fuzzy theories. As this method remains unrecognized in the eyes of the law today, the aforementioned main gate of Higashiyama Johen was applied to a government office under the name of a poster tower. Properly speaking, snow load, seismic load and wind load are fuzzy loads. Big earthquake or big typhoon which we have not ever experienced, may visit near future. We can design the building more rationally and more economically by using fuzzy construction method against these fuzzy load.

It is very interesting that our precursors have designed wooden buildings based on a kind of fuzzy theories. The writer
indicates the possibility that the fuzzy technique is applied to the development of new construction method of modern wooden buildings. Should all buildings be designed with full reliability against the catastrophic snowfall or typhoon that anyone can not predict if it will visit once a hundred years? We conclude that a future design method should introduce the fail-safe design technique from rational and economical points of view, that the construction method of Hanegi suggests.

REFERENCES

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