Folded roof house: Design solution to optimize the environmental condition with generic equipment and techniques

Kaoru Suehiro¹ ²  |  Noriko Suehiro¹  |  Yoko Masuda³  |  Kazuko Ito⁴  |  Kazuhide Ito⁵

¹NKS Architects, Fukuoka, Japan  
²Faculty of Human-Environment Studies, Kyushu University, Fukuoka, Japan  
³TOURI-SHA Structural Design Office, Osaka, Japan  
⁴WEST Japan Engineering Consultants, Inc., Fukuoka, Japan  
⁵Faculty of Engineering Sciences, Kyushu University, Fukuoka, Japan

Abstract
We covered a rectangular site in a residential area oriented at a 45° angle to the north, and rotated the roof of the second floor on top of the rectangular first floor and created a large window on the side at the south corner. To realize an open interior with a limited footprint, we created a single-volume space connecting the first floor to the second floor with stairs. The timber frame of the second floor sits on the concrete box of the first floor. The stiff timber box consists of a folded roof and exterior walls to realize a large pillar-free space. We set the main windows higher to maximize the effect of natural light, placed eaves in front of the large window to block direct sunlight, and used slit windows between the first and second floors to promote natural lighting and ventilation.

KEYWORDS  
environmental optimization, environmental simulation, passive design, small residential house, sustainable design, timber construction

FIGURE 1  Overall interior view of folded roof house in Kasuga
1 | INTRODUCTION

We present a small house for a family of four, specializing in architectural environmental engineering. The primary design objective for this house was to optimize the indoor environmental quality within a limited site space and budget. Along with the social trend of sustainable and energy efficient private houses in Japan, relatively high percentage of new houses has been equipped with sophisticated new technologies and energy creation systems. However, these systems are generally costly and the design of houses is not harmonized with these technologies. We believe that the "folded roof house" is a design solution that optimizes the pleasantness, comfort, environmental conditions while using generic equipment and techniques, and achieved an architectural expression together with technologies. Figure 1 shows overall interior view of folded roof house in Kasuga.

2 | ARCHITECTURAL CONCEPT

2.1 | Site planning

The single-family house is located in a suburban residential area, where many private houses are situated side by side on similar housing lots (Figure 2). The rectangular lot with 176.7 m² size is oriented approximately 45° to the north. Because the carport with about 5.7 m depth needs to be along the street, the house has to be situated very close to the southern boundary, just a step behind the neighboring houses. We considered the solution of rotating the second floor by 45° on top of the first floor to open a large window at a higher level facing south (Figures 3 and 4).

2.2 | Floor planning

We produced a single continuous interior volume to create an open indoor environment in the limited footprint of 79.2 m² and accommodate different places for the family’s daily life. The floor of the main living space was raised approximately 800 mm from the entrance and the ground floor level, on which a bathroom, a toilet and a kitchen are located. A large and symbolic dining table as the meeting place of the family is located next to the kitchen and its height is just 300 mm above the kitchen counter top (Figure 1). The main living space is connected to the second floor with large steps as benches or shelves. The second floor is divided by furniture into two spaces for bedrooms. These different levels help maintain a distance between various places in the volume (Figures 5–7).

2.3 | Structure system and roof construction

The foundation and the exterior walls of the first floor are made of 250 mm thick concrete, while the structure of the second floor and other components are all made of small-size timber materials with 120 mm dimension prevalent in the market. We also used the conventional technique and the generic steel joints for the timber construction, which local carpenter can afford. The stiff timber box
structure consists of the folded roof panels and the exterior wall panels realize a pillar-free space of 7.7 m x 10.2 m. While we set the section of the folded roof with right angle to make the construction easier, the whole roof slants about 10° for drainage and scale adjustment of interior space. There were some joints with unusual angles at the meeting points of folded roof and walls, and we made 3D models and drawings to explain them for carpenters (Figures 8 and 9).

2.4 | Natural lighting and ventilation

We designed the house to have sufficient natural daylight and ventilation, meanwhile the area of the window surface was minimized to reduce thermal loss. We set four main windows at higher level to maximize the natural lighting effect, from which the light comes in along the pitched ridges of the folded roof. The large window has eaves to block direct sunlight during summer season, two ventilation windows lit from the both side of the central ridge, and the small triangular skylight facing north is at the peak of the roof (Figures 10 and 11). The second-floor timber box was set on arms popping out from the first-floor concrete box. We used the slit between the two boxes as horizontal windows. Ventilation windows perforated the house in many directions and at different levels; this was effective at not only exploiting various wind directions but also realizing ventilation caused by temperature difference (Figure 12).

2.5 | Insulation and air conditioning

We set the insulation specifications to optimize the thermal performance. The first-floor concrete was covered with insulation and worked as heat storage to stabilize the interior thermal conditions. The second-floor timber panels were filled with onsite forming insulation to prevent heat bridges and condensation. It is generally difficult to realize an effective heating system for the winter for an interior volume with a high ceiling. The underfloor heating system consists of an energy-efficient air conditioning unit, and a circulation fan keeps the first floor warm. The air flow along the folded roof created by the circulator fan minimizes the non-uniformity of air temperature in the space. Because of the exterior heat insulated concrete wall with large heat capacity and under floor air conditioning system, it is possible to maintain comfortable indoor thermal conditions all year round (Figure 13).

2.6 | Conditions of sustainability

Owing to these environmental design solutions, the observed data showed mostly expected results with regard to energy consumption. If solar cell panels are introduced on the roof in the future, the house will be a zero-energy building. The introduced generic technologies and construction systems were quite effective to keep the building cost reasonable. However, sustainable building issues are not dependent only on technologies. Although the house looks quite closed from the street, the inhabitants can see the sky and truly experience the outside environment. The distinctive folded roof,
altered light conditions, and stepped floor levels differentiate the character of each place in the continuous interior space. These places can be used flexibly according to future changes in the family’s lifestyle. It is crucially important for a house being sustainable to keep having affection from residents. We expect the house to keep accommodate their happy and comfortable life for longer period.

### 3 | ENGINEERING CONCEPT

The design of a personal residential house from an engineering point of view seems to be very similar to school education. The success or failure of education becomes apparent by degrees obtained over a long period of time and has a dominant influence on life. Individual abilities and demands are diverse, but there is also an averaged-common basis to adapt to society and culture. In this regard, failure is not permitted in school education. It becomes difficult to challenge existing experiences and standardized theories. The design of a personal residential house, especially environmental design, may be the same.

A house, along with the family living there, exists on the same time scale as life. Introducing state-of-the-art environmental control systems and equipment can improve the initial environmental performance, but these technologies may become obsolete within a few years and may need to be replaced with new state-of-the-art technology. The basic strategy of a small residential house design may be to adopt a reasonable structure on firm ground, reduce the external heat load by improving the thermal insulation and airtightness, and utilize sunlight, outdoor air, and groundwater as necessary. In subsequent phases, we should consider introducing reasonably and efficient active-type environmental facilities from a comprehensive viewpoint.

Based on this engineering design concept, we introduced the following environmental control devices/methods.

(i) Utilization of well water;
(ii) Introduction of horizontal slit-type windows for natural ventilation and ambient daylight;
(iii) Materials-integrated photocatalytic oxidation reaction activated under visible light;
(iv) Floor heating system with an underfloor chamber using a heat pump-type air conditioner;
(v) Air circulator fan on the ceiling to manage heterogeneous air and temperature distributions;
(vi) Exterior heat insulation finish.

The following performances were analyzed by using environmental simulation techniques:

(i) Optimization of the window opening position by solar radiation and indoor light environment analysis;
(ii) Natural/cross-ventilation design supported by computational fluid dynamics (CFD) simulation.
(iii) Optimization of opening position of horizontal slit-type windows by using wind pressure coefficient analysis with CFD;
(iv) Annual heat load calculations to optimize the thermal insulation and natural/mechanical ventilation.

As the numerical simulation/analysis tools provide deterministic information for environmental conditions, the flexibility of design might decrease greatly when aiming at environmental optimization. Against this trade-off problem, collaboration between architect, environmental engineer, and resident, from the design stage until the completion, enables harmonization of architectural design and environment.

4 | CONCLUSION

For this residential house, the indoor air/thermal environment and utility demands (e.g., electricity and tap water usage) have been continuously measured immediately after the families moved in. The owner, an expert on environmental engineering, has been investigating ways of environmentally optimizing the family’s lifestyle. Continuous efforts to optimize the indoor environmental quality immediately after the completion of construction lead to the pleasantness of this residential house.

5 | PROJECT DATA

Main structure: Reinforced concrete (RC) structure + Wooden (in part)
Site area: 176.76 m²
Building area: 79.20 m²
Gross floor area: 102.49 m²
Completion: August 2015
Location: Kasuga-shi, Fukuoka
Construction company: Kawakita Construction, Co. Ltd.

REFERENCES


FIGURE 10 Living room view

FIGURE 11 Triangular skylight

FIGURE 12 Horizontal slit-type windows for natural ventilation and ambient daylight


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