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Steel-Framed Houses, Environmentally Friendly Houses

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Abstract

In steel-framed houses, coated steel sheets substitute for the wooden structural members of conventional wooden houses. The advantages of steel-framed houses over wooden houses such as greater durability, better recyclability and prevention of deforestation make them desirable as a new, environment-friendly house construction method. This paper clarifies environmental issues surrounding houses by comparing the performances of steel and wooden houses.

1. Introduction

The steel-framed house is a house whose wooden structural members are replaced by coated steel sheet shapes of about 1.0 mm thickness. This construction method was commercialized about 25 years ago in the United States. In 1992, President Clinton issued an order banning the felling of trees in national forests. The resultant skyrocketing increase in the cost of lumber accelerated the spread of steel-framed houses in the United States, where about 100,000 steel-framed homes were built in 1998. In Japan, many wooden houses collapsed in the Great Hanshin Earthquake of 1995. This disaster triggered the construction of steel-framed houses in Japan. About 400 steel-framed houses have been built to date in Japan. **Photo 1** shows a steel-framed house under construction with Nippon Steel's cooperation in Kitakyushu City.

One reason for the rapid penetration of steel-framed houses in the United States is the fact that the American Iron and Steel Institute (AISI) proactively advertised steel-framed houses as "environmentally-friendly houses." For example, the AISI held the International Conference on Steel in Green Building Construction in Florida in March, 1998. At the meeting, people from many parts of the world presented their reports from the standpoint that steel-framed buildings, mainly houses, are sustainable in terms of durability, environmental burden, recyclability and energy conservation, among other factors. The present authors and other researchers from Japan also attended the conference[1].

Table 1 compares a steel-framed house and a wooden-framed (two-by-four) house in the quantities of structural members used. The first floor of each house is either framing or concrete. The wooden-framed house is built with about 17 m^3 (7.5 tons) of wood[2], which requires about 1,000 to 1,500 m^2 of forest to be felled. The steel-framed house replaces this amount of wood by about 5 tons of recyclable steel. In this way, the steel-framed house is an environmentally-friendly house from the viewpoint of conserving a valuable forest resource. It must also be evaluated in relation to durabil-

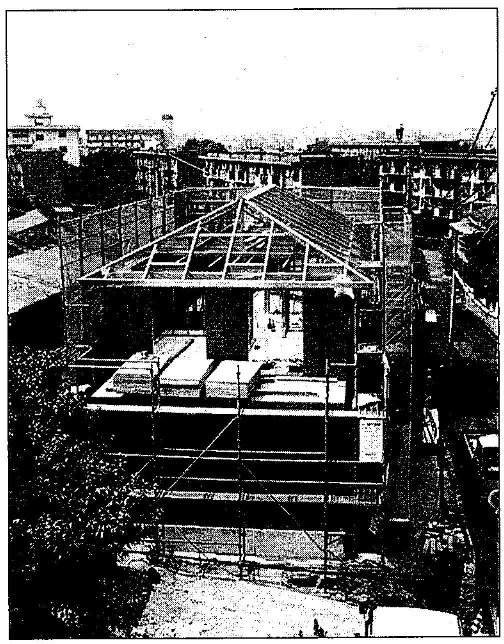

Photo 1 Steel-framed house under construction

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Table 1 Quantity comparison of steel-framed house and wood-framed house

First-floor structure		Steel-framed house		Wood-framed house	
		Framing	Concrete	Framing	Concrete
Unit quantity	m^3/tsubo	—	—	0.440	0.402
	kg/tsubo	124.5	111.3	184.8	168.8
Unit quantity comparison		0.67	0.66	1.0	1.0
Quantity(120m^2)		4.98ton	4.45ton	17.6m^3	16.1m^3

ity, energy conservation, and other factors.

Of the steel-framed house construction technologies under joint development by Nippon Steel and the Kozai Club, this report introduces those related to environment protection and describes their application.

2. Durability

One of the reasons for the collapse of many wooden houses in the Great Hanshin Earthquake of 1995 was the rot and termite damage of wood. Wood-framed houses are said to last 25 years without special measures (e.g., use of larger columns). Given the adverse effect of termiticides on the health of people, it is considered difficult to make any drastic improvements in this respect.

Steel-framed houses are believed to last more than 50 years if properly built, because:

(1) Coated steel sheets with excellent durability are used.

(2) Airtightness and thermal insulation performance are high, and damp-proofing is perfect.

The life of steel-framed houses can be quantitatively determined by clarifying the correlation between the corrosive environment in the house and the corrosion rate (corrosion weight loss) of the metal coating on the steel used to build the hosue[3,4]. **Photo 2** shows a steel-framed house built at the foot of Mt. Aso in Kumamoto Prefecture and used by Nippon Steel to make various measurements.

The corrosive environment in the house is measured by four atmospheric corrosion monitor (ACM) sensors installed outdoors (below the eaves) and indoors (in the wall cavity of the bathroom and at the back of the ceiling). The correlation between the corrosive environment and the corrosion rate (coating corrosion weight loss) is separately measured by ACM sensors and coated steel sheet samples, each coated with the Kanto loam and sea salt, in environment-simulated box and exposing them at the Tokyo University of Mercantile Marine in Shizuoka City, Shizuoka Prefecture. **Fig. 1** shows the meas-

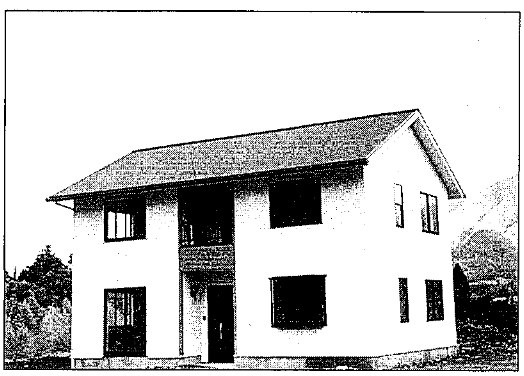
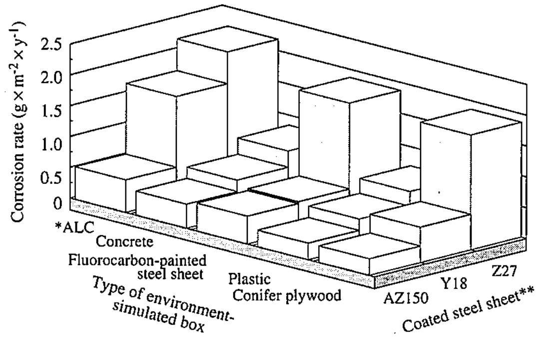


Photo 2 Steel-framed house where corrosive environment is measured



*ALC: Autoclaved lightweight concrete
**Coated steel sheet: AZ150: Coated with 55% aluminum-zinc alloy, Y18: Coated with Zinc-5% aluminum alloy, Z27: Coated with zinc

Fig. 1 Corrosion rate of coated steel sheet specimens after 12-month exposure test in environment-simulated box (outdoor, Kanto loam: 10 g/m^2, sea salt: 0.1 g/m^2)

urement results. The measurements made with the simulating containers revealed the correlation between the corrosive environment and the corrosion rate of the specimens. Since the steel-framed house is fully protected against dew condensation, the ACM sensors installed in the house produce very small output signals. When estimated from the above-mentioned correlation, the corrosion rate is extremely small, suggesting that the steel-framed house has a life of more than 100 years.

In this way, the steel-framed house is by far more durable than the wood-framed house. This contributes to reduction in the environmental burden in the stages of construction, demolition and disposal.

3. Comparison of Environmental Impacts by Life Cycle Assessment (LCA)

This chapter plots the life cycle assessment (LCA) of wood and steel not for houses but it is limited to their structural members. The assessment is limited to the environmental impacts of the materials in the manufacturing and disposal stages of the life cycle of the house, and excludes the environmental impacts of construction, service, and maintenance stages of the life cycle. This is because the assessment is reduced to the differences in the materials for structures.

3.1 Assessment method

The LCA method was based on the research framework and evaluation factors studied by a group under the leadership of Leiden University[5]. Inventory data were all quoted from published litetatures[6], except for the data for the steel production process. The LCA software tool SimaPro 3.0[7] of Pre Consultants BV, the Netherlands, was used. The assessed model products is described below.

(1) Wood[8]

The wood was that sawed and dried at the site in Canada or the United States. Its air-dry specific gravity and moisture content were put at 0.45 and 15%, respectively. With attention focused on the quality of forest resources to be felled, the proportion of unsustainable forestry (logging in natural forests and old growth forests) was evaluated[9]. Application of a chromated copper arsenate (CCA) preservative was assumed as treatment against fungi and termites. (This treatment was assumed to be applied to the foundation alone or 5% of all structural members.) The recycle rate of the materials after the disposal of the house was estimated at 51%[10].

(2) Steel

The weight of steel equivalent to 1 m^3 of wood was set at 283.0

kg (Table 1). The steel production process was based on the interim results of the Japan standard data being internally studied by the Japan Iron and Steel Federation[11]. The recycle rate of steel scrap obtained after the disposal of the house was estimated at 93%[10].

Of impact categories adopted in the Leiden approach[5], those for which evaluation factors were not fully developed and those not suited for the comparison of wood and steel were excluded. This left the three impact categories "resource depletion", "global warming effect", and "human toxicity". Furthermore, the category "waste emission" designed to represent the present construction waste problem in Japan and the category "energy consumption" often addressed by simplified LCA methods were added. These five impact categories are discussed here.

The life of the steel-framed house was put at 50 years, and the life of the wood-framed house was put at 25 years (Chapter 2). The comparison required the normalization of environmental impacts for a period of 50 years. This means that the steel and wood go through one and two life cycles, respectively. In other words, the environmental impacts of 2 m^3 are presented for the wood.

3.2 Results of LCA

The five LCA categories are compared in **Table 2** and Figs. 2 to 6.

(1) Waste emission

The volume of waste generated after the demolition of the house is compared for 50 years (**Fig. 2**). The waste volume is 0.978 m^3 per 2 m^3 of wood and is about 1/400 of that for steel. The waste generation can be reduced by about 3 tons, 7 m^3, or 30% each time a wood-framed house with a total floor area of about 120 m^2 is rebuilt.

(2) Human toxicity

Human toxicity is evaluated on the basis of permissible intake per day and a simple exposure model. The unit is kg. A toxic impact of 60 kg is equivalent to the permissible intake per day of one person with a weight of 60 kg. From **Fig. 3**, it can be concluded that the toxic of wood is about 10 times higher than that of steel. The disposal of timbers treated against fungi and termites accounts for 80% of the toxicity impact of wood. The exposure model assumes a path for the release of the toxic substances to the soil where the amount of exposure to the human body is smallest. There is a high probability that the model underestimates the actual situation, because the toxic substances will be dispersed in air if the treated timbers are burned in the open air.

The steel production process accounts for one-third of the toxicity impact of steel. The remaining two-thirds is the total of SO_x, NO_x, and CO emissions from the combustion of fossil fuels in the transportation and many other processes as is the case with wood. One of the initial concerns was the toxicity of chromate. The chromate is released to the surrounding environment in only trace amounts during the use of the house and is rendered harmless in the recycle process of steel sheet after the disposal of the house. If all of the chromate is assumed to be dissolved in the soil, its toxic impact is only one-twentieth of the total toxic impact.

Table 2 Overall comparison of environmental impacts

Item	Unit	Steel	Wood
Waste emission volume	m^3	0.0025	0.978
Human toxicity	kg	1.91	19.12
Resource depletion	$\times 10^{-11}$	7.28	32.80
Energy consumption	MJ	3,637	12,038
Global warming effect*	CO_2 equivalent kg	680	899 (212)

*Global warming effect is value in case a. Value enclosed in parentheses is that of case b.

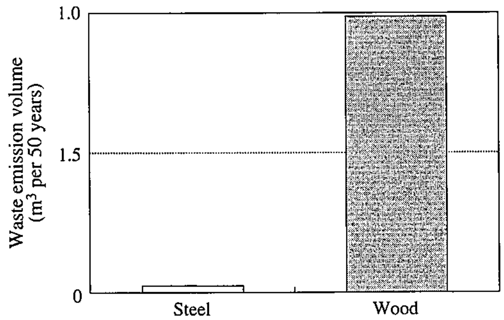


Fig. 2 Impact comparison of waste emission volume

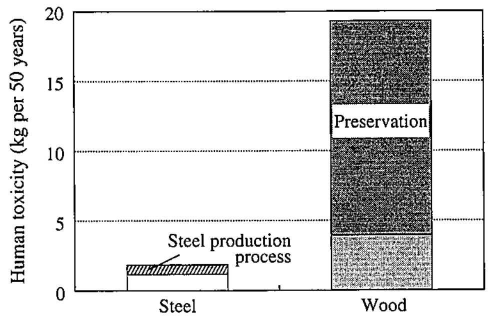


Fig. 3 Impact comparison of human toxicity

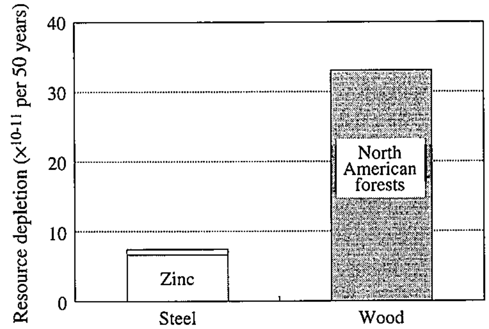


Fig. 4 Impact comparison of resource depletion

(3) Resource depletion

The impact on resource exhaustion is measured by the ratio of a used resource to the total amount of that resource. **Fig. 4** shows that the impact of steel is about one-fourth of that of wood. The impact of wood on resource depletion is mostly accounted for by the consumption of North American natural forests and old growth forests. The consumption of zinc minerals accounts for as much as 98% of the impact of steel on resource depletion.

One problem with these results is whether or not the exhaustion of forest resources can be handled on the same type of impact as that of mineral resources. Natural forests, which are unsustainable forest resources, can be renewed after a few centuries, but mineral resources cannot be renewed in a mere few centuries. The destruction of natural forests has large secondary effects, such as destruction of the ecosystem and reduction in diversity of biological resources. Mineral resources have a high possibility of being replaced by other resources and are limited in the range of their secondary effects. The issue of logging has been reduced to the consumption of exhaustible resources.

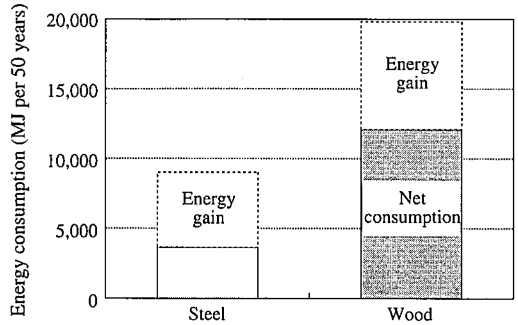


Fig. 5 Impact comparison of energy consumption

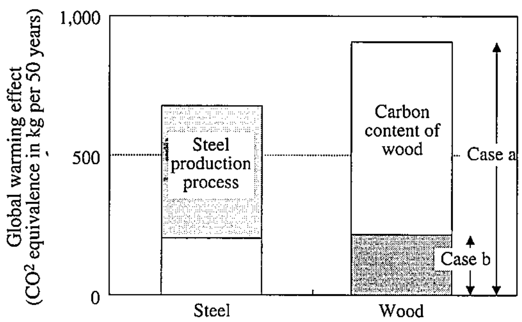


Fig. 6 Impact comparison of global warming

Whether or not this approach is fair and rational is still open to discussion.

(4) Energy consumption

Fig. 5 shows that the energy consumption of steel is about one-third of that of wood. There are no rules for handling recycle in LCA. Here, energy recovery during recycle (utilization of waste timber as fuel or regeneration of steel) is taken as an energy gain, and the material production energy less the energy gain is taken as net energy consumption. Steel is assumed to be a blast-furnace product, and the blast-furnace product is assumed to be regenerated as an electric-arc-furnace product of lower energy consumption. This energy difference is regarded as energy gain.

This LCA study equated the heating value of wood with energy because wood is recycled as fuel. Whether or not to include the heating value of wood in energy consumption is an open question in the world, however. Plastic products are similarly handled. The heating value of naphtha as raw material for plastics is usually regarded as energy consumption.

(5) Global warming effect

The impact of steel and wood on global warming is compared in **Fig. 6**. This comparison is made in two cases: case a in which the CO_2 emissions derived from the carbon contained in wood are included and case b in which the CO_2 emissions are not included. The impacts of steel and wood are 680 and 899 kg, respectively, in the former case and are 680 and 212 kg, respectively, in the latter case. The unit is one kilogram of CO_2 equivalent. The impacts of all greenhouse effect gases are converted into the impact of CO_2.

How to treat the CO_2 emissions of wood is a matter of opinion. Case a is based on the idea: "The absorption of CO_2 by forests is especially a natural action, and only the process of CO_2 being finally released by logging arises from human activities. Mature forests do not have any more ability to fix CO_2, and logging is equivalent to emitting CO_2". Case b is based on the idea: "Wood is obtained by fixing CO_2. Even when CO_2 is finally released by incineration or decay, the balance becomes zero". At the present stage, we cannot say which case is objectively correct.

3.3 Summary

The differences in environmental impacts between different materials of structural members have been evaluated above. Steel scored better than wood for all of the five categories compared with respect to their impacts. This is probably because the excellent environmental performance properties of steel, such as "high recyclability", "no decaying even under Japan's climatic conditions" and "no destruction of forests", are correctly reflected in the evaluation.

4. Energy Conservation

Thermal insulation performance is important from an energy conservation point of view. Japan's Housing Loan Corporation uses energy conservation as one of the preferential conditions for loan interests. Higher "energy conservation standard for the next generation" is currently under consideration. Therefore, there is an obvious trend that thermal insulation performance is ever increasing in importance.

The heat loss from the inside of the house occurs through the various parts. If the house is given no thermal insulation at all, for instance, the heat lost through parts other than such openings as windows and doors is said to account for about 70% of the total heat loss[12]. This accentuates the importance of improving the thermal insulation of wall, floor and roof members in the house.

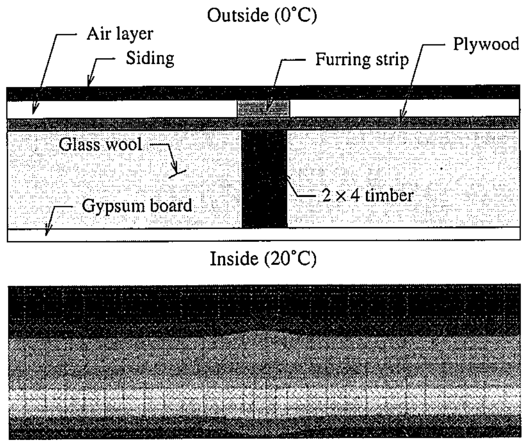
The steel-framed house forms a closed space by walls, and therefore offers higher thermal insulation performance and air tightness than the conventional Japanese wooden house. In fact, the steel-framed house was developed and spread in the cold regions of North America; thus energy-saving has been paid an attention in its development process.

Steel has a thermal conductivity 300 to 400 times as high as that of wood and thus calls for a design method that gives consideration to the heat loss through coated steel sheet shapes.

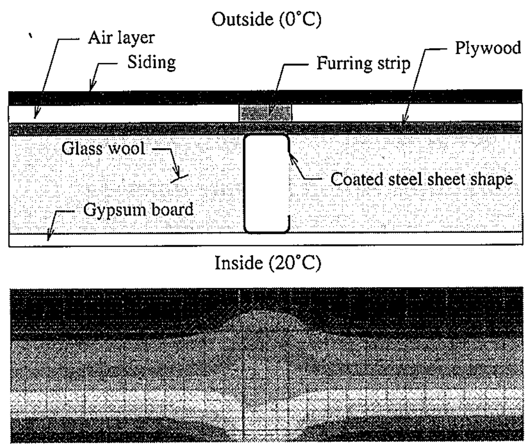
Figs. 7 (a) and 7 (b) show the heat transfer analysis results (temperature distributions) of typical walls. Inside and outside room temperatures were set in the analysis 20°C and 0°C, respectively. The thermal insulation method employed was "cavity insulation" with the thermal insulation material placed in wall cavities. Wood and a coated steel sheet shape are used as structural member in Figs. 7 (a) and 7 (b), respectively. From Fig. 7 (b), it is evident that the cold outside air flows through the steel shape into the room. This phenomenon is called a thermal bridge (or cold bridge) and causes the heat loss.

The steel-framed house adopts "exterior insulation" as a solution to the heat loss problem[13,14]. The exterior insulation method can prevent the heat flow through a wall by installing an insulation board or the like on the outside of the wall. **Fig. 7 (c)** shows the analysis results of such an exterior insulation wall. The thermal bridge through the steel shape is sharply reduced. The exterior insulation can also prevent the dew condensation within the wall. As is clear from Fig. 7 (a), the wall cavity temperature with the cavity insulation is lower than that with the exterior insulation as shown in Fig. 7 (c), even when the structural material is wood. As a result, the dew condensation tendency is increased in cavity insulation, decreasing the durability of the framework.

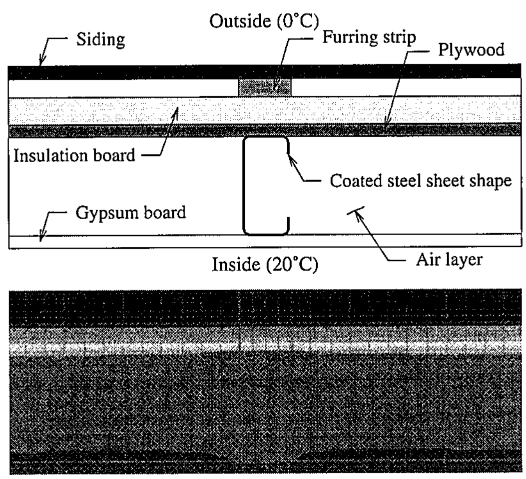
The exterior insulation is adopted in this way for the steel-framed house to achieve greater energy savings as well as higher durability.



(a) Cavity insulation of wall in two-by-four house



(b) Cavity insulation of wall in steel-framed house



(c) Exterior insulation of wall in steel-framed house

Fig. 7 Analysis results of thermal insulation performance of exterior walls

5. Conclusions

The environmental aspects of the steel-framed house developments have been discussed above. Since steel-framed houses increased to account for 10 % of the single-family houses in the United States, the logging industry in Canada was alarmed at the situation and initiated the ATHENA Project to study the environmental burdens of wooden houses and steel houses[15]. In Japan, a large timber importer, a Japanese pamphlet[16] of the ATHENA Project was prepared and distributed to home builders across the nation. Steel is increasing its competition with wood in the residential construction industry.

Nippon Steel is working jointly with two-by-four homebuilders on the development of the hybrid construction method that uses wood and steel in appropriate places[17]. This does not highlight the advantages of steel alone, but is essential for environmental compliance. We will continue our research in this respect.

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