USING CO_2 EMISSION QUANTITIES IN BRIDGE LIFECYCLE ANALYSIS

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ABSTRACT: In recent years, new types of bridges have continued to appear with the development of new construction technologies and functional requirements in Japan. However, lifecycle analysis was rarely used to evaluate such new types of civil infrastructures. In this research, a general lifecycle assessment methodology is modified for evaluating new types of civil infrastructures. Furthermore, this modified methodology is applied for comparing the lifecycle performance of a conventional bridge and a minimized girder bridge, which is a new type of bridge constructed in the second Tokyo-Nagoya-Osaka expressway. Finally, accelerated exposure tests of steels and seismic isolation bearings is addressed and test results on the durability of these materials is used to perform the lifecycle analysis.

INTRODUCTION

As bridge construction in most industrialized nations accelerated from 1950, a great number of bridges are becoming older than the 50 year design life? The comparison of construction periods of bridges in the USA and Japan is shown in Fig. 1 (OECD 1992). Although the bridges of Japan are comparatively younger than those of the USA, the maintenance and replacement burden is increasing gradually (Nishikawa 1994). When most bridges become older, not only do the maintenance costs increase tremendously, but huge investment is also needed for replacing older bridges. Replacement of urban bridges is a difficult issue as the area surrounding them is normally developed for commercial or official purposes (Novick 1990). This is especially true in the case of a large metropolitan city like Tokyo in Japan. There are various focuses of the research on lifecycle cost of bridges. Ellis et al. (1995), Mohammadi et al. (1995) and Chang and Shinozuka (1996) focused on the development of conceptual models of bridge lifecycle cost. Cady and Weyers (1984), and Frangopol et al. (1997) carried out studies on lifecycle cost based on deterioration of existing bridge structures. Liu and Itoh (1997) used optimization of maintenance strategies for lifecycle management of network level bridges. Efforts are ongoing in the USA to reduce the lifecycle cost by the use of high performance steel (Wright 1998). However, difficulties still prevail in predicting lifecycle cost of bridges with required accuracy. Lifecycle cost may be useful for comparative studies if consistent methods are followed to evaluate various alternatives.

Besides the lifecycle cost, the environmental impact is important in infrastructure management. Since environmental impact assessment of large projects is made mandatory in many countries, various researches attempt to evaluate environmental impacts from infrastructure lifecycle. Global warming is one major threat to the earth and this is caused by emissions of greenhouse gases. Under the United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol adopted in third conference of parties (COP3), has set quantitative targets to reduce the greenhouse gases by 2012. In Kyoto protocol, Japan has committed to reduce the greenhouse gas at 1990 levels by 6% in 2012 (UNFCCC 1997). The Kyoto protocol treaty has not been ratified and may not go into effect. However, all sectors need to reduce the emission of greenhouse gases, including the construction sector. Several studies have been started in Japan to calculate the share of greenhouse gases and energy consumption from the construction sector of Japan, mainly by the Public Work Research Institute (PWRI) and Japan Society of Civil Engineers (JSCE). Global environmental impact has been considered as one of the selection factors for bridge type by Itoh et al. (1996). Horvath and Hendrickson (1998) considered comparison of steel and reinforced concrete bridges with respect to environmental impacts from lifecycle. Also, high performance coating systems are being developed in the USA to reduce various environmental hazards from bridge paints (Calzone 1998).

Considering future problems in bridge management, a concept of Minimum Maintenance Bridge is proposed for a service life of 200 years by Nishikawa (PWRI 1997a). This bridge type is conceptualized by making critical components of the bridge more durable and prevents more frequent deterioration phenomena. Frequent maintenance requirements such as painting, expansion joint replacement, and deck rehabilitation are minimized in the proposed Minimum Maintenance Bridge by using currently available technologies such as use of long life painting, durable types of expansion joints and pre-stressed concrete (PC) deck slab. The Japan Highway Public Corporation (JH) developed a new type of bridge, a minimized girder bridge using PC deck slab and it is now under construction in the second Tokyo-Nagoya-Osaka expressway. The minimized girder bridge uses the same concept in part as the minimum maintenance bridge, but has an expected service life of 100 years.

This paper presents the features of the Minimized Girder Bridge and comparison of its lifecycle cost and environmental impact with the conventional bridge. The more common causes of bridge damage

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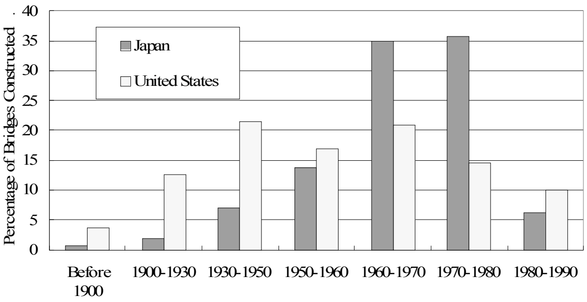


FIG. 1. Comparison of Construction Period of Bridges in U.S.A and Japan

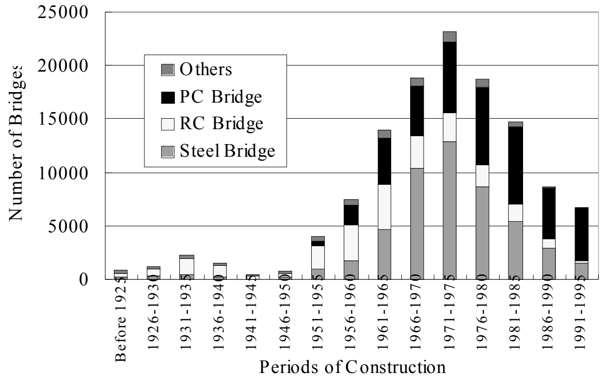


FIG. 2. Construction Periods of Bridges in Japan

are analyzed and methods are proposed to prevent critica damaging factors. Implementing concept of such Minimized Girder Bridges in practice is expected to enhance technical development by identifying specific requirements for bridge longevity. Additionally, in order to obtain the fundamental data of environmental effects on steel bridge members, the corrosion of the steels and rubbers under cyclic environmental changes is investigated with the accelerated exposure test. The results are compared with those of the outdoor exposure tests carried out in Japan.

CURRENT SITUATION OF JAPANESE BRIDGES

About 130,000 have a length of more than 15m and are located in national highways and prefectural roads. The total length of these bridges is 7,481,000 m. The steel bridges are more common and are typically longer. The pre-stressed concrete (PC) bridges are the second most common as well as second in length. Since PC bridges have been constructed only after 1950s, this shows the preference of PC bridges over steel and reinforced concrete (RC) bridges in recent years. The period of construction of the existing bridges is shown in Fig. 2. This figure shows that the majority of highway bridges were constructed after 1954 when a nationwide road construction program started in Japan. The bridge construction concentrated heavily in the years 1960s and 1970s. As average bridge service life is commonly believed to be 60 years, the majority of bridges of Japan will be at the end of their service life in the coming decade, requiring huge investments in major rehabilitation and replacement.

When major maintenance actions are not enough to remedy impaired structural and functional performance of a bridge, replacement is the only viable option to make the bridge serviceable. Knowing the reasons for replacement and failure of bridges is important to develop new methods of design for durability. Surveys were carried out to find the number of bridges replaced in Japan during 1966-1996 by PWRI (PWRI 1997b). The survey results were made available for the interval of every 10 years in 1977, 1987 and 1997 respectively. A total of 5,159 bridges were replaced during the period of 1966-1996. The various causes of bridge replacement are: (1) damage of superstructure; (2) damage of substructure; (3) insufficient load carrying capacity; (4) functional problems; (5) improvement work; (6) countermeasure against seismicity; and (7) damage due to disasters other than earthquake.

The damage of the superstructure is due to corrosion of steel, cracking and spalling of concrete, damage of deck slab, or deterioration of bearings. Displacement of abutments and piers, cracking of abutment/pier and foundation scour are the causes of substructure damage. Insufficient load carrying capacity is caused due to insufficient design load and increased weight of vehicles allowed on the road. This is mainly due to revisions of the allowable live load in the code of practices. The various reasons for functional problems are narrow bridge widths, traffic congestion, insufficient height clearances, and insufficient clearance under the girder. Most improvement work included the improvement of road alignment, river conservation, and urban planning. Countermeasures against seismicity were carried out to cope with the revised design load for earthquakes. Among various reasons listed above, the first two reasons (i.e. damage of superstructure and damage of substructure) are related to the physical life of a bridge. The other reasons like functional problems and improvement work correspond to the deficiency in the functional design of the bridge. Dunker and Rabbat (1995) identify insufficient deck width, insufficient load carrying capacity, and deterioration of substructure, superstructure and deck as the three main causes of deficiencies of US bridges where 40% of 600,000 bridges are either functionally or structurally deficient. The insufficient deck geometry and insufficient load carrying capacity is related to functional deficiency, such problems are abundant in bridges constructed before 1970. The condition is similar in Japan where most of bridges built before 1960 needed improvement work mainly due to functional problems.

Road and bridge planning and design methods have been improved considerably in the past decades. As a result, the functional problems like narrow width, alignment improvement, river conservation, urban planning, and so on are expected to reduce in bridges constructed in the future. The design specification and code of practices has been improved from 1970s after the introduction of design codes for earthquake resistant design of highway bridges in 1971 in Japan. The significant improvement in

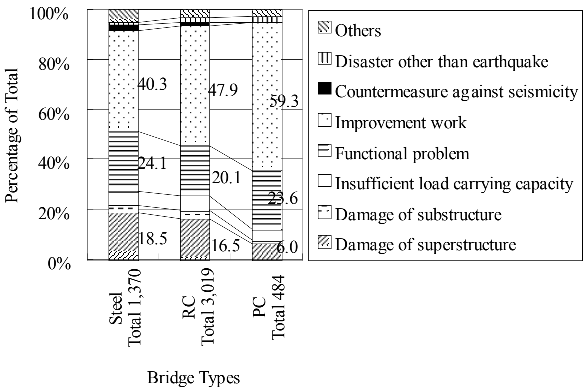


FIG. 3. Reasons for Replacement of Bridges in Japan

TABLE 1. Dimensions of Bridges Using in Comparison

Bridge types (1)	Construction methods (2)	Span arrangement (m) (3)
PC simple pre-tensioned T-girder bridge	Truck crane method	8@18.8
PC simple box girder bridge	Support erection method	3@50.0
Steel simple non-composite box girder bridge	Bent method	3@50.0

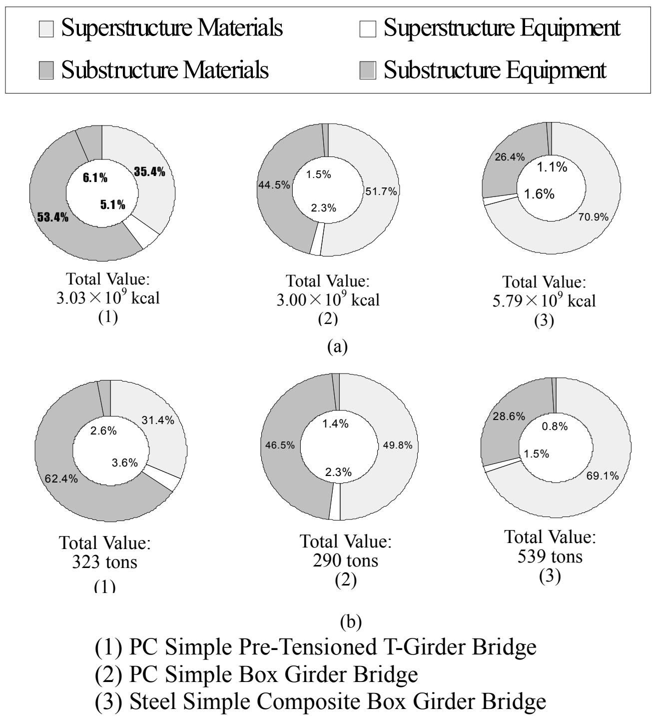


FIG. 4. Proportions of Environmental Impacts from Superstructure and Substructure (a) Energy Consumption; (b) CO_2 Emission

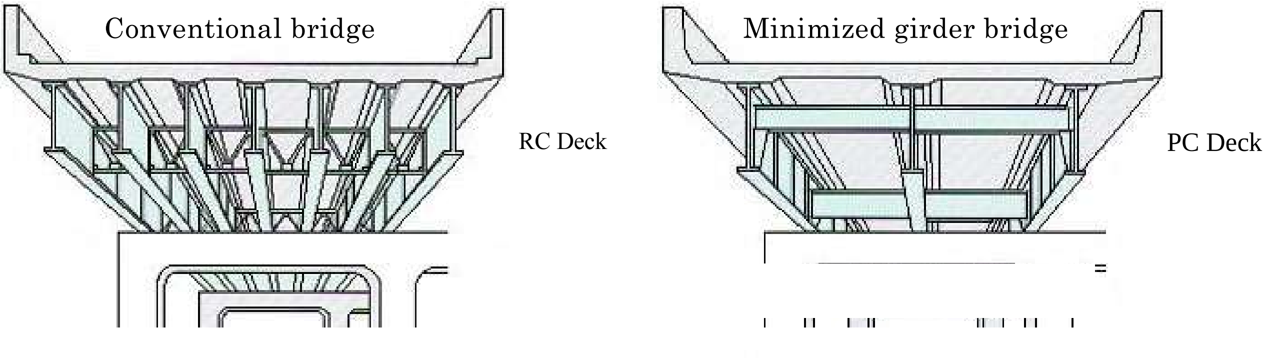
the design codes and inclusion of seismic design criteria is hoped to reduce problems like insufficient load carrying capacity and countermeasure needed against seismicity. Small and Cooper (1998) show a continuous reduction of structurally as well as functionally deficient bridges in the USA from 1982. They attribute technology advancement and better understandings of bridge-load-environment interaction as the main reasons of reductions of bridge deficiency. If other reasons of bridge deficiencies are corrected, the physical issues of bridge damage need to be prevented to lengthen the service life of a bridge. It is because deterioration phenomena can not be prevented by improving only the code of practices and design specifications. Considering only physical reasons of bridge replacement, damage of superstructure is the main cause of bridge replacement. Fig. 3 shows the percentages corresponding to the various reasons of replacement of steel, RC, and PC bridges. Among the 1,370 steel bridges replaced during the survey period, 18.5% of them were due to damage of superstructures. Over 16.5% of the 3,019 RC bridges were replaced due to damage of superstructure. Since PC bridges were constructed only from 1950s, only few of them have been replaced up to 1996. The majority of PC bridges were also replaced due to functional problems and road improvement work. Only about 6% of the PC bridges were replaced due to the reason of superstructure damage.

LIFECYCLE ANALYSIS OF BRIDGE

Environmental Impacts from Superstructure and Substructure at Construction Stage

The proportion of environmental impacts from superstructure and substructure in the total environmental impacts from the bridge at the construction stage is calculated for comparison. The energy consumption and CO_2 emission are used as the environmental impact increases. A bridge having a length of 150m and 12m width is considered. Table 1 shows the construction methods and span arrangements of the bridge types that are used in this investigation. These bridge types are taken among the 30 cases of various bridge types and span arrangement obtained with the system. The abutments are inverted T-type with 6m height. T-type piers having each of 12m height are considered.

Figs. 4(a) and 4(b) show the proportions of energy consumption and CO_2 emission, respectively, from the superstructure and substructure in cases of PC Simple Pre-tensioned T-girder Bridge, PC Simple Box Girder Bridge, and Steel Simple Non-composite Box Girder Bridge. In case of the PC Simple Pre-tensioned T-girder Bridge, the environmental impacts on the substructure are larger than that on the superstructure. It is because this bridge has a short span length of 18.8m, and the number of piers is large. In case of the PC Simple Box Girder Bridge, the span length is 50m, and the environmental impacts on the superstructure are larger than that of



(a) Conventional Bridge (b) Minimized Girder Bridge

FIG. 5. Conceptual Graphs of Conventional Bridge and Minimized Girder Bridge

TABLE 2. Bridge Data for Lifecycle Assessment

	Conventional Bridge	**Minimized Girder Bridge**
Superstructure type	Steel continuous non-composite I-girder bridge	
Bridge length (m)	199.7	173.4
Bridge width (m)	15.73	15.5
Spans (m)	40.5, 42.6, 49.5, 67.1	39.6, 40.3, 42.5, 51.0
Deck type	RC deck	PC deck
Deck thickness (cm)	24	27
Number of main girders	6	3
Height of main girder (m)	2.5	2.9
Connection	Bolt connection	Welding on site

TABLE 3. Lifecycle Assessment Phases for Development of Bridge Technology

Phases	**Tasks**
1	Defining the goals of lifecycle assessment, decomposing the lifecycle into several stages, and identifying the elemental items at each lifecycle stage
2	Studying the approach to determine the resource consumption of each elemental item, and collecting the unit value for each assessment purpose
3	Applying the lifecycle assessment for the conventional bridge technology, and determining the parametric values
4	Applying the lifecycle assessment for the new bridge technology, and comparing with the conventional bridge technology

the substructure. The reason behind it is that the number of piers is less and the span length of superstructure is also high. Finally, in case of Steel Simple Non-composite Box Girder Bridge, the proportion of the environmental impacts from the superstructure is larger than that of the PC Simple Box Girder Bridge of the same span arrangement. This is because the superstructure is made of steel which has larger energy consumption and CO_2 emissions than the concrete. Among three bridge types, the steel bridge has the highest environmental impact value in comparison to other two PC bridges. This is due to the use of more amounts of steel in case of steel bridge that has higher unit impact values. The energy consumption from construction equipment is in the order of 5% in these bridge types. The total CO_2 emissions from construction equipment are in the order of less than 5%. This shows that the major portion of environmental impact of these bridges is due to the making of construction materials.

Minimized Girder Bridge

A minimized girder bridge is a relatively new type of bridge. Fig. 5 shows the conceptual graphs of a conventional bridge and a minimized girder bridge. It has been noted that the minimized girder bridge does not have enough redundancy in USA. However, from the fatigue test of PC deck slab, The Japan Highway Public Corporation (JH) adopted this type of bridge convincing that the good condition can be maintained in the lifetime of 100 years. In order to study the lifecycle performances of this newly developed type of bridge, two typical bridges are formulated under similar conditions. One is designed and constructed under conventional bridge technologies and the other is a minimized girder bridge. Both bridges are assumed to be located in Nagoya, Japan under the same environmental conditions. The basic data of these two bridges are shown in Table 2. Because the lengths and widths of two bridges are not exactly same, the calculation values of costs and environmental impacts in this paper are in form of the unit area of the bridge deck for the purpose of comparison.

TABLE 4. Maintenance Cycles of Bridge Components (year)

Components	Service life
Pavement	15
PC deck	50
RC deck	30
Painting	20
Expansion joint	20
Support	30

Modified Lifecycle Assessment for Bridge

In this research, the lifecycle Assessment (LCA) methodology was modified to be applicable for bridge technologies, which has four phases including the main tasks shown in Table 3.

At phase 1, the lifecycle of a bridge covers several stages, including the planning, design, construction, service and monitoring, maintenance, and demolition stages in which different organizations and engineers take the key roles. In this research, however, the bridge lifecycle represents the construction stage, the maintenance stage and the replacement stage only, which covers the major on-site activities and resource consumption. The lifecycle assessment goals are specified as the lifecycle environmental impact and the lifecycle cost.

At phase 2, the main tasks are to determine the quantity of each elemental item, and the unit value for each assessment goal. The volume or weight of materials is calculated for a bridge lifecycle based on the design manuals and interviews with bridge engineers. Similarly, the duration of construction equipment used in various construction, maintenance, and demolition activities are found by the databases depicting the past experiences and interview. The CO_2 emission from the unit volume or the unit weight or the unit duration is taken from the results of studies by PWRI (1994) and JSCE (1997). The PWRI values are obtained with input-output analysis in Japan. The JSCE values are calculated with LCA method in which all processes are accounted for to make the product. This LCA method is supplemented by the input-output analysis. Since JSCE values are new and cross-checked with both LCA and the input-output analysis, the JSCE values are used in this research to calculate the lifecycle environmental impact of bridges. However, the unit CO_2 emissions of some construction materials that are not included in JSCE analysis are calculated according to the PWRI values. The unit cost value is determined according to several cost manuals and the interview.

At phase 3, a conventional bridge is studied from the lifecycle environmental impacts and costs point of view, and the possible effects of the assessment scopes, the setting assessment period, the recycling, and so on. These selected scopes are usually considered to directly relate to the functions of a bridge.

Finally, at phase 4, the new type of bridge technology, minimized girder bridge, is assessed in detail and the results are compared with the conventional bridge with the similar conditions. The conclusions should be stated from the viewpoints of lifecycle assessment goals to comment the application prospect of this new bridge technology.

Assumption for Lifecycle Assessment of Bridge

In this study, it was assumed that the bridge lifecycle contains the construction, maintenance, and replacement stages. The lifecycle environmental impact and cost could be summed as follows:

$$E_t = E_c + E_m + E_r + \sum p_d E_d \quad (1)$$

$$C_t = C_c + C_m + C_r + \sum p_d C_d \quad (2)$$

where, E_t and C_t are the environmental impact and cost within the whole lifecycle of a bridge, respectively; E_c and C_c are the environmental impact and cost from the construction stage, respectively; E_m and C_m are the environmental impact and cost from the maintenance stage, respectively; and E_r and C_r are the environmental impact and cost from the replacement stage, respectively. On the other hand, E_d and C_d are respectively the lifecycle cost and environmental impact due to the damage of structures by events or disasters such as earthquake, traffic accident, and so on, and p_d is the probability of the events occurring.

The lifecycle assessment at the construction stage needs the primary data of a bridge including its cross-section data, span arrangement, superstructure type, substructure type, foundation type, and others. In the previous research, a bridge type selection system was developed to determine these primary data and the environmental impact and cost from the construction stage of a bridge with the selected type (Itoh et al. 1996, Itoh et al. 2000b). These outputs are parts of the lifecycle environmental impact and cost of a bridge. The environmental impact from the construction stage contains the environmental impact from both the construction materials product and the construction machinery, and can be formulated in the following equation:

$$E_c = \sum_{n=1}^{N} M_n U_{CO2}(n)$$

$$+ \sum_{j=1}^{J} (G(j) U_g(j) + \frac{W_w(j) U_w(j)}{W_l(j)}) W_h(j) \quad (3)$$

where, M_n and $U_{CO2}(n)$ are the quantity of one kind of construction

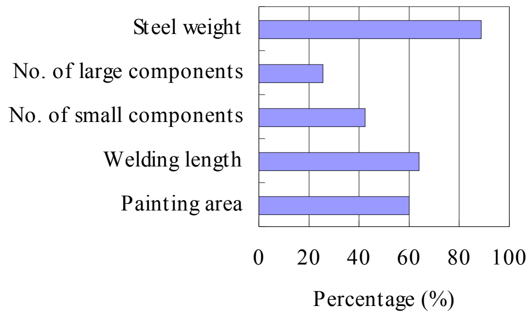


FIG. 6. Material Consumption of Minimized Girder Bridge versus Conventional Bridge

material (n) and the CO_2 emission due to its consumption per unit; $G(j)$, $U_g(j)$ and $W_h(j)$ are the energy consumption per hour, the CO_2 emission due to the consumption of energy per unit, and the working hours for one construction machine (j); and $W_w(j)$, $U_w(j)$ and $W_l(j)$ are the weight, the CO_2 emission per weight, and the service life for one construction machine (j), respectively. The symbols N and J are the numbers of kinds of materials and machines, respectively. Similar formulations were used for calculating the environmental impact from both the construction materials and the construction machines during the maintenance and demolition stages. The cost during the construction stage covers the costs of construction materials, construction machine, and labor, which were determined according to the design and construction manuals of bridges and the interviews with the practical bridge engineers.

The maintenance requirements and specific techniques of a bridge or its components are determined according to the periodic inspection and the further testing in detail if necessary. Based on the existing bridge inspection manual and information from the practicing engineers, eight types of bridge components needs more maintenance. These are the pavement, deck, painting, expansion joint, support, girders, guard fence, and piers (abutment). This structural deterioration is due to the service and material aging. In this research, only five bridge components were considered for the lifecycle evaluation, namely the pavement, deck (PC deck and RC deck), painting, expansion joint, and support. The girder was not included because it was thought it was not necessary to repair when keeping the good condition of painting. The maintenance period (service life) of these components were assumed as the mean values in Table 4. This was differenced from hearings with the practicing engineers and referring to publications, such as Nishikawa 1994.

The environmental impact and cost from the maintenance stage are formulated in the following equations:

$$E_m = \sum_{i=1}^{5} (E_{iMm} + E_{iMw}) \frac{L}{L_i} \tag{4}$$

$$C_m = \sum_{i=1}^{5} (C_{iMm} + C_{iMw}) \frac{L}{L_i} \tag{5}$$

where, E_{iMm} and C_{iMm} are the total environmental impact and cost during the maintenance stage from the construction materials for the bridge component i, respectively; E_{iMw} *and* C_{iMw} are the total environmental impact and cost during the maintenance stage from the construction machinery for the bridge component i, respectively; and L and L_i are the analysis period and the service life of the bridge component i, respectively. Estimations of costs and environmental impacts from maintenance activities of these bridge components are difficult for the time being and the values used in this research were adopted from the previous literature and interview with practicing bridge engineers (Itoh et al. 1999).

There have been several common bridge replacement methodologies, such as closing the traffic while replacing, constructing a temporally bridge instead of the existing bridge under the replacement, and closing a part of the bridge and keeping the other part open for service. The selection of such a replacement method is dependent on the bridge type, the site condition, the traffic condition, and so on. To determine the environmental impact and cost due to the replacement activity, the consumption of materials and machinery of each replacement operation are essential. However, such data has not been sufficiently summarized to be able to be utilized in these calculations. The environmental impact and cost from the replacement stage in this research were assumed to be constants without considering the possible change due to the different methods. These are formulated as follows:

$$E_r = E_{rd} + E_c \tag{6}$$

$$C_r = C_{rd} + C_c \tag{7}$$

where, E_{rd} and C_{rd} are the environmental impact and cost due to the demolition of the old bridge, respectively. These values are difficult to estimate. In this research, only the environmental impact from the demolition machine was considered, and the demolition cost was obtained from the interview. The demolition costs of several past demolished bridges in Nagoya city were collected and represented by per unit of deck area. The average value and the standard deviation of these demolition costs were 226 thousand Yen/m^2 and 41 thousand Yen/m^2, respectively. This average value was about the 2.5 times of the construction cost of a new bridge per square meter of the deck area, which was near the number of 2.8 concluded in

TABLE 5. Comparison of Materials Needed for Bridge Deck Construction (/m^2)

	Conventional Bridge	Minimized Girder Bridge
Concrete Volume (m^3)	0.249	0.296
Form (m^2)	0.717	1.480
Weight of reinforcement (kg)	62.062	75.432
Weight of PC steel (kg)	0	10.214

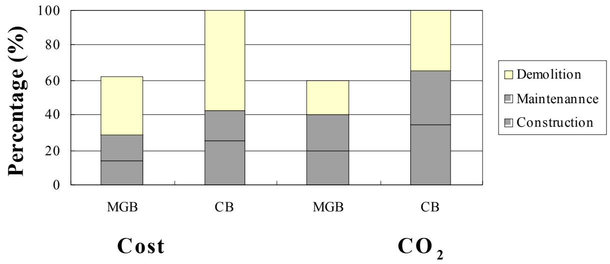


FIG. 9. Comparison of Annual CO_2 Emission and Cost

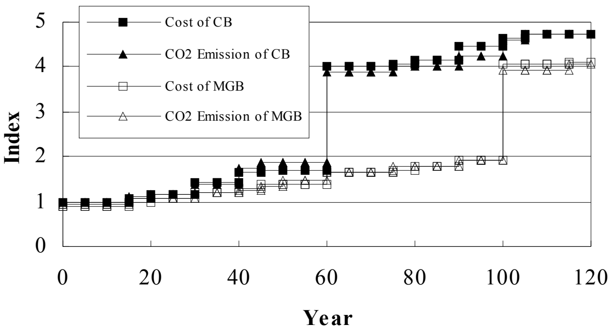


FIG. 8. Comparison of CO_2 Emission and Cost (Index: nondimensionalized by the values of

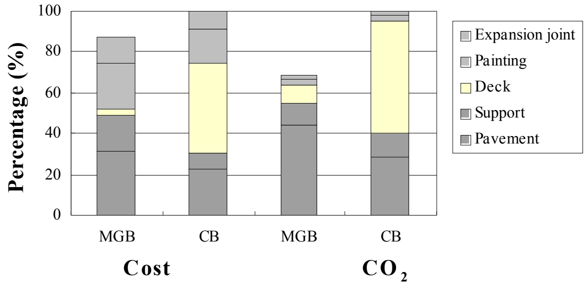


FIG. 10. Comparison of CO_2 Emission and Cost due to Maintenance Activity

TABLE 6. Replacement Cycles of Bridge Components (year)

	Short service life	Standard service life	Long service life
Pavement	10	15	20
PC deck	40	50	60
RC deck	20	30	40
Painting	15	20	25
Expansion joint	15	20	25
Support	25	30	35

other research (PWRI 1997). The environmental impact and cost due to the construction of a new bridge are considered as part of the environmental impact and cost at the demolition stage, however they are not included into the demolition cost if only one lifecycle is analyzed.

Although the effects due to some events, p_dE_d and p_dC_d , shown in Eqs. (1) and (2), should be included in LCA, these were not taken into account in this study since the appropriate data, especially on p_d , were not found.

LCA Application for Conventional Bridge and Minimized Girder Bridge

According to the statistics and reports from the fabrication factories and the construction sites, during the fabrication and construction stage of the conventional bridge and the minimized girder bridge of which the basic data were summarized in Table 2, the material consumptions were obtained. Fig.6 shows the material consumption of the minimized girder bridge versus the conventional bridge. The steel weight, the number of larger components, the number of small components, the weld length and the painting area of the minimized girder bridge were as low as 89%, 25%, 43%, 64%, and 60% of the conventional bridge, respectively. In particular, the number of large components decreased due to the lower number of main girders. Due to the decreases in volume and weight of the materials, the fabrication cost of a steel minimized girder bridge was 60% of the fabrication cost of the conventional bridge approximately.

In addition, as shown in Fig.7, the CO_2 emission of the minimized girder bridge is only about 94% of the conventional bridge. The main girder, deck, and pavement contributed the major portion of CO_2 emission during the construction stage of both the conventional bridge and the minimized girder bridge. The CO_2 emissions of most bridge components were also smaller in the case of the minimized girder bridge. However, the CO_2 emission of the deck was larger for the minimized girder bridge than that of a

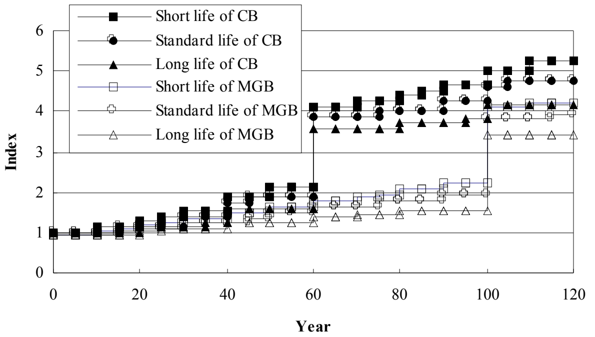


FIG. 11. Effect of Service Life onto Lifecycle CO_2 Emission

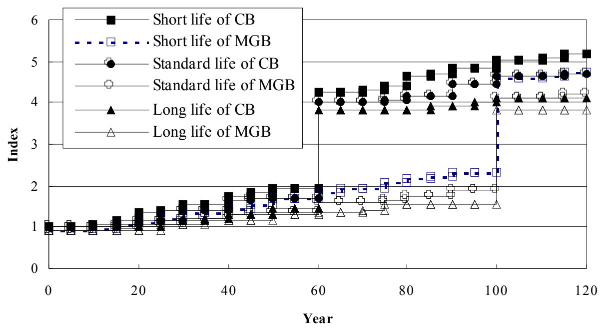


FIG. 12. Effect of Service Life onto Lifecycle Cost

FIG. 13. Combined Cyclic Corrosion Test Instrument

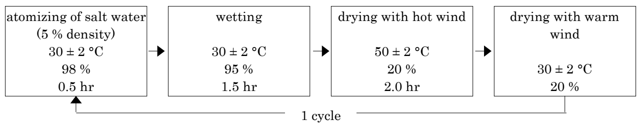


FIG. 14. Condition of Accelerated Environment Cycle

conventional bridge. Table 5 compares the volumes and weights needed per square meter of deck for the two types of bridges. It is obvious that a minimized girder bridge takes more concrete, forms, reinforcement, and PC steel to construct a unit area of deck due to its higher thickness and the higher requirement of the structural rigidity.

Fig.8 shows the comparison of the lifecycle CO_2 emission and cost between a conventional bridge (CB) and a minimized girder bridge (MGB). The indices of the CO_2 emission and cost at a certain year represent the relative values by taking the CO_2 emission and cost values of the conventional bridge at the construction stage as one. The increasing tendencies of the cost and CO_2 emission with time were very similar for both the conventional bridge and the minimized bridge. However, the indices of the CO_2 emission and the cost of the conventional bridge at the end of 120 years were higher than those of the minimized girder bridge, although all indices at the starting year of both bridge types were close. The differences can double when the service lives are between 60 and 100 years.

Further comparison is carried out for the annual CO_2 emission and cost within one life cycle of the conventional bridge and the minimized girder bridge from various lifecycle stages. Fig.9 shows the relative percentages by taking the total lifecycle CO_2 emission and cost values of the conventional bridge as one. The differences between these two bridge types for given lifecycle stages were rather large and did not depend on the cost or for the CO_2 emission. The prolonged service life of the minimized girder bridge takes an important effect to increase these differences.

Fig.10 shows the relative percentages of the annual cost and CO_2 emission of the conventional bridge and the minimized girder bridge from the maintenance performance of each bridge component by taking the total cost and CO_2 emission values of the conventional bridge as one. The minimized girder bridge could reduce by about 15% and 30% of the annual cost and CO_2 emission of the conventional bridge induced due to the maintenance activities. In the case of the conventional bridge, the deck maintenance was very costly and contributed more CO_2 emission than other bridge components. However the pavement became a more noticeable component for the minimized girder bridge. The percentages of the costs from various maintenance activities are different for a conventional bridge and a minimized girder bridge. The similar conclusions could be stated for the environmental impact.

Further comparison study on the CO_2 emission and cost consumption from each lifecycle stage has been performed by considering three cases of replacement cycles (short service life, standard service life and long service life) of each major bridge component as shown in Table 6. For the purpose of comparison, it was assumed that all bridge components have the same rate of deterioration for all these three cases.

Fig.11 and 12 represent the CO_2 emission and cost consumption from the whole lifecycle stages of both the CB and the MGB in three cases of service lives (short service life, standard service life, and long service life) by taking the CO_2 emission and cost consumption of the conventional bridge at the construction stage as 1, respectively. It was assumed in the calculation that the components were completely reconstructed at the end of each components service-life. The conventional bridge contributed more CO_2 emission and required unclear costs than the minimized MGB girder bridge in each of the three cases of replacement cycles. It is also found that prolonging the service life of a bridge component is invaluable for both bridge types from the viewpoints of the lifecycle CO_2 emission and the lifecycle cost.

In order to conduct the performance-based design for bridges considering LCA, more accurate durability information of each component of bridges is necessary. The lifetime of each component of bridge should be estimated based on the survey of existing bridges and experimental data. One of the effective methods to obtain the fundamental durability data in the short time is the accelerated exposure test. In the following section, the accelerated exposure test under conduct is dealt with and the results are compared with the outdoor exposure test.

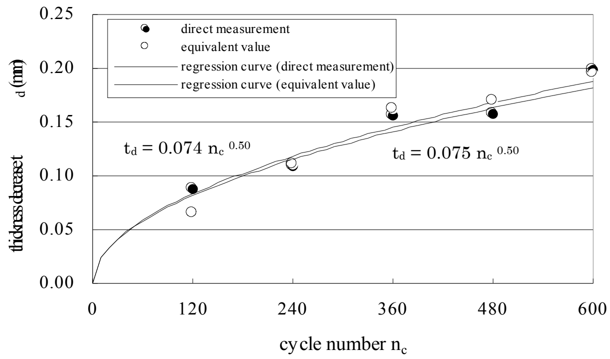


FIG. 16. Mean Thickness Decrease

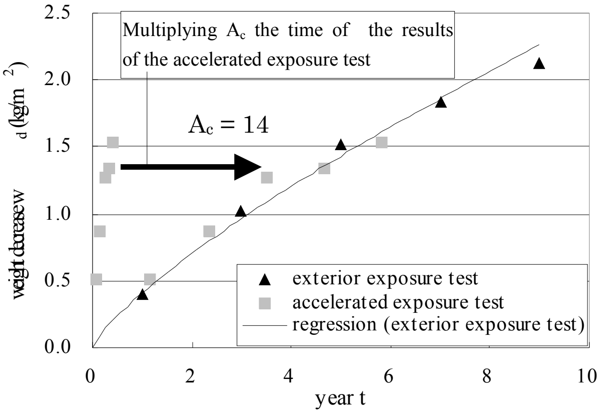


FIG. 17. Acceleration Coefficient

ACCELERATED EXPOSURE TEST OF STEELS

The objectives of this accelerated exposure test address the investigations of the environmental effects on the durability of the steel bridge members and the proposal of a LCA strategy including the evaluation of the cost due to the environmental effects. The time histories of the weight and thickness reduction of the steel plates due to the rust are investigated. Additionally, the results of the accelerated exposure tests are compared with those of the outdoor exposure tests, and the relationship between these two tests is clarified. A formula to predict the steel member corrosion due to fog with salt is proposed. The fundamental durability data are important to conduct the performance-based design considering LCA.

Method of Experiment

A Combined Cyclic Corrosion Test Instrument made by SUGA TEST INSTRUMENTS Co.,Ltd., shown in Fig. 13 was used in the research. This equipment can automatically operate and control the condition of atomizing of salt water, temperature, and humidity in arbitrary orders and combinations. This equipment has a rectangular space 2,000 mm long, 1,000 mm wide and 500 mm high, where the test pieces are arranged. A maximum of 188 test pieces of 70 mm wide, 9 mm thick and 150 mm long can be arranged in the chamber.

15 blast furnace steels and 15 electric steels standardized by Japan Industrial Standard (JIS) and called SM490 (yield stress of 325 MPa) were selected as test pieces of the experiment. These surface of each steel was grit blasted called with No.50 grit as S-G50 in JIS.

The condition of environment cycles adopted in this experiment is shown in Fig.14, refereed to as an S6-cycle. The experiment was carried out for 600 cycles (about 150 days). The S6-cycle was proposed by the Ministry of International Trade and Industry and was specified in JIS. The past research for painted steels concluded that the result of the accelerated exposure test under this cycle was highly correlated to outdoor exposure tests. Although the test pieces in this test were uncoated, the S6-cycle was used since the appropriate cycle for the uncoated steels has not been found.

In the research, 3 test pieces were taken out from the test instrument every 120 cycles (about 30 days), and the corrosion product was removed by boiling the pieces with ammonium citric acid and thiourea. The weight and the thickness of test pieces were measured.

Experimental Result

The mean weight decrease of each of the 3 blast furnace steels and that of each 3 electric steels are shown in Fig.15 respectively. The relation between the weight decrease by corrosion and time is expressed with Eq. (8).

$$w_d = kt^n \tag{8}$$

Where, w_d is the weight decrease (kg/m^2), t is time (year) and k and n are constants. The cycle number n_c is used instead of t in this

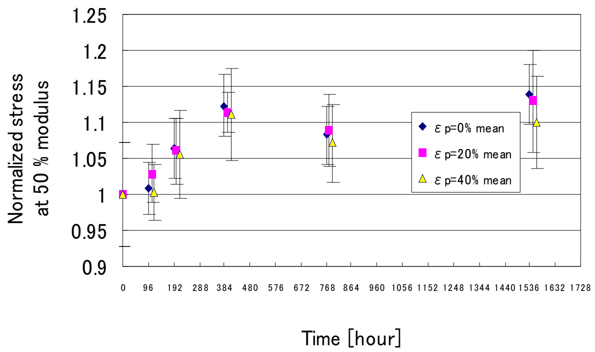


FIG. 19. Ozone Effect on Deterioration of a Rubber

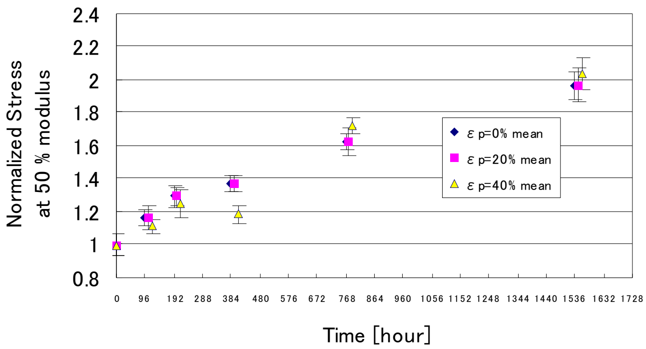


FIG. 20. Heat (70°C) Effect on Deterioration of a Rubber

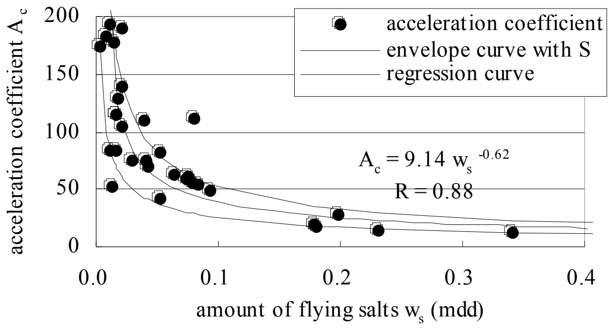


FIG. 18. Relation between Amount of Flying Salt and Acceleration Coefficient

study, and the relation between the weight decrease w_d, and n_c is shown in Fig.15. The constants in Eq. (8) were obtained with the least-squares method, and the R in Fig. 15 is a correlation coefficient. Due to the corrosion, the weight of the test pieces decreased as cycles increased, and the gradient of the weight-decrease curve tended to decrease. The weight decrease of electric steels at each cycles is 2-8 % larger than that of blast furnace steels approximately. It is thought that the difference is small enough to be negligible.

The mean thickness decrease was calculated with (the weight decrease) / (density of the steel) / (surface area of the test piece), assuming that the distribution of the corrosion product was uniform. This method had been adopted by the Ministry of Construction and used to evaluate the results of the outdoor exposure tests. (Ministry of construction, 1992) For comparison, using the micrometer, the thickness decrease of the test pieces was measured directly. The thickness decrease t_d obtained with these two methods is shown in Fig.16. The blank circle denotes "equivalent thickness decrease" calculated from the weight decrease and the filled circle is the thickness decrease obtained with the direct measurement. Both results agreed. The regression curves are also illustrated in Fig.16. Similarly to the case of the weight decrease, the data were well fitted with the involution function on n_c.

Acceleration Coefficient

The Ministry of Construction carried out the outdoor exposure tests of steels as well as the investigation of the amount of flying salt (fog salt) at 41 sites in Japan. (Ministry of Construction, 1992) Results of 31 tests for 9 years and results of the accelerated exposure tests for 600 cycles (about 5 months) were compared, and the acceleration coefficient A_c was calculated in this paper. The acceleration coefficient was obtained with (time scale of outdoor exposure test) / (time scale of accelerated exposure test) as shown in Fig.17, and is the parameter for connecting the results of the accelerated exposure test to the phenomena at the sites of the outdoor exposure test. The calculated acceleration coefficients were 6 to 75 at the seaside area, 70 to 178 at the urban/rural area, and 53 to 189 at the mountainous area. These results mean that the acceleration coefficient does not always depend on the regional characteristics.

Flying Salt and Acceleration Coefficient

The relation between the amount of flying salt w_s and the acceleration coefficient is shown in Fig.18. The solid line is a regression curve of the acceleration coefficient with the involution function,

$$A_c = 9.14 w_s^{-0.62} \tag{9}$$

where w_s is the amount of flying salt (mg/dm^2/day, mdd) and A_c is the acceleration coefficient. The dotted line is an envelope curve with the standard deviation S. The correlation coefficient R was 0.88, thus the relation between the amount of flying salt and the acceleration coefficient can be expressed as Eq. (9).

Presumption of Amount of Thickness Decrease

Using the equation $t_d = 0.0074 \times n_c^{\ 0.50}$ shown in Fig.16 and Eq.

(9), the following equation was obtained:

$$t_d = 0.094(w_s^{\ 0.62} t)^{0.5} \tag{10}$$

where t_d is the amount of thickness of steels decrease (mm). Eq.(10) enables the prediction of the mean thickness decrease due to the flying salt. In the accelerated exposure test, the test pieces were mounted vertically in the experiment instrument, thereby Eq.(10) can be applied to only vertically placed members of bridges.

ACCELERATED EXPOSURE TEST OF SEISMIC ISOLATION RUBBER BEARING (MENSHIN BEARING)

The environmental durability of rubber bearing as used for seismic base-isolation bearing is also important for the lifecycle analysis of bridges. It is said that the cost of the base-isolation bearing is about 8％ to 10 % of the initial total cost of bridges in Japan. In order to obtain the fundamental data and perform the lifecycle analysis of bridges considering the atmospheric corrosion resistance performance of 100-years, the accelerated exposure tests of rubber material of bearings with long term is now exposure under way in various conditions (i.e. ozone atmosphere, heat, sun, cyclic atomizing of salt water, and cyclic acid rain).

The deterioration of a rubber due to ozone is shown in Fig.19. The vertical axis is the stress at 50% strain, normalized with the stress at the initial state, and ε_p is the pre-strain. The normalized stress was thought to converge around 400 hours of the accelerated exposure test. On the other hand, the deterioration due to heat considering the temperature change, shown in Fig.20, seemed to increase even after 1536 hours.

CONCLUSIONS

This research aims to develop a lifecycle assessment methodology for the civil infrastructures and apply it for the development of a new type of bridge named minimized girder bridges. In order to obtain the fundamental durability data, the accelerated exposure tests were carried out to clarify the environmental effects on corrosion growth of steels and seismic isolation rubber bearings. The followings are the main conclusions in this study.

(1) The modified lifecycle assessment methodology was applied for assessing the lifecycle CO_2 emission and cost of the minimized girder bridges, and the results are compared with a conventional bridge.
(2) A conventional bridge contributes more CO_2 emission and has a higher cost than a minimized girder bridge.
(3) The accelerated exposure test of steels resulted that the amount of the weight decrease became large and this decrease was able to be expressed with mathematical function.
(4) The difference between characteristics of blast furnace steels and electric steels (recycled material) for corrosion was examined with the accelerated exposure test, and the weight decrease of electric steels was a little bit larger than that of blast furnace steels.
(5) A simple formula to predict the mean thickness decrease due to fog salt for vertically placed steels was proposed, using the results of the accelerated exposure test.
(6) Some useful results from accelerated exposure test of seismic base-isolation rubber bearing pad were obtained to apply the lifecycle analysis of bridges. It was found that ozone, heat, and sun exposure are main factors for the deterioration of rubber bearing.

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NOTATION

The following symbols are used in this paper :

A_c = acceleration coefficient;
C_t, E_t = total lifecycle cost and total environmental impact;
C_c, E_c = lifecycle cost ant environmental impact at construction stage;
C_d, E_d = lifecycle cost and environmental impact due to disaster;
C_{iMm}, E_{iMm} = total environmental impact and cost during maintenance stage from construction material for bridge component i ;
C_{iMw}, E_{iMw} = total environmental impact and cost during maintenance stage from construction machine for bridge component i ;
C_m, E_m = lifecycle cost and environmental impact at maintenance stage;
C_r, E_r = lifecycle cost and environmental impact at replacement stage;
C_{rd}, E_{rd} = lifecycle cost and environmental impact due to demolition;
$G(j)$ = energy consumption per hour of construction machine j ;
L = analysis period of LCA ;
L_i = service life of the bridge component i ;
M_n = quantity of construction material n ;
n_c = cycle number;
p_d = probability of event occurring ;
t = time;
t_d = thickness decrease of steel;
U_{CO2} (n) = CO_2 emission due to consumption of material n ;
$U_g(j)$ = CO_2 emission due to consumption of energy for construction machine j;
U_w (j) = CO_2 emission per unit weight of machine j;
$W_h(j)$ = working hours for construction machine j ;
$W_l(j)$ = service life of construction machine j ;
$W_w(j)$ = weight of construction machine j ;
w_d = weight decrease of steel;
w_s = amount of flying salt; and
$_p$ = pre-strain of rubber.