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LIFECYCLE ENVIRONMENTAL IMPACT AND COST OF BRIDGES

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Abstract

In the recent years, the environmental problem such as the global warming has become a serious issue in the whole world. Researchers and practical engineers in civil engineering have to pay enough attention to the environmental impact in addition to the function, safety, cost and aesthetics at all lifecycle stages of a civil infrastructure. In this study, an approach is proposed to predetermine the CO_2 emissions and costs of bridges from the construction, maintenance and demolition stages based on an available system developed for the bridge type selection. In addition, a case study on the lifecycle environmental impact and cost of two typical types of bridges is carried out to identify the specific effects of each lifecycle stage and others. Finally, this approach is applied for comparing the lifecycle environmental impact as well as the lifecycle cost from both the conventional bridge and the minimum maintenance bridge proposed by the Public Works Research Institute (PWRI).

KEYWORDS: *lifecycle evaluation, global environment, cost analysis, minimum maintenance bridges*

1. Introduction

Due to the use of construction equipment and the consumption of fossil fuels during the related activities, emissions of greenhouse gases are caused from the construction activities of a bridge. For example, the manufacturing of cement, a major construction material, contributes significant portion of carbon dioxide (CO_2) emissions (IPCC 1997). It contributes about 2.4% of total CO_2 emissions from industrial sectors in the world. The construction sector is mainly associated with the natural resources consumption and industrial activities. The construction sector in Japan is contributing about 3.10×10^{14} kcal of energy consumption and 30.3 million metric tons of CO_2 emissions per year (PWRI 1993). Compared to the total national figure, this makes about 8% and 10% of total energy consumption and CO_2 emissions, respectively. Figures 1(a) and 1(b) show the shares of energy consumption and CO_2

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emissions from the civil engineering construction, building construction and maintenance to total annual energy consumption and CO_2 emissions of Japan. Since all civil engineering, building construction and maintenance are related to construction activities, the total of construction activities accounts about 19% of total national annual energy consumption and 23% of total national annual CO_2 emissions respectively. Other sectors include transportation, industries, land use and so on.

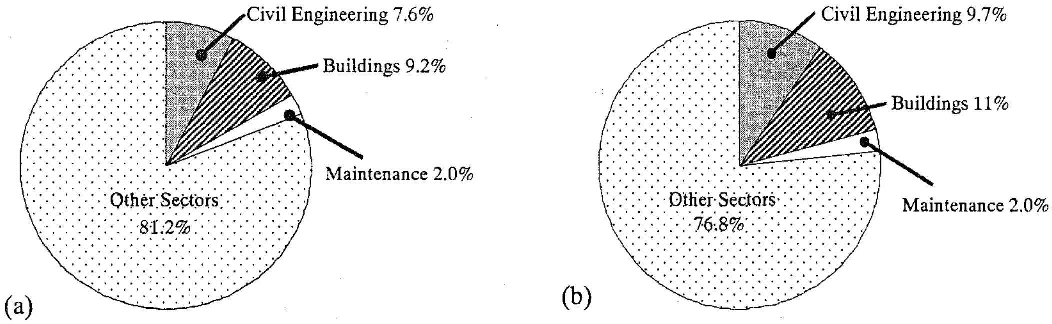

Figure 1. Sector Shares of Environmental Impact in Japan
(a) Energy Consumption (b) CO_2 Emission

As the bridge construction in most industrialized nations accelerated from 1950, a great number of bridges will become older than 50 years in the following years. The comparison of construction periods of bridges of the USA and Japan is shown in Figure 2 (OECD 1992). Though the bridges in 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 the maintenance cost increases tremendously, but huge construction cost is also needed for replacing old bridges.

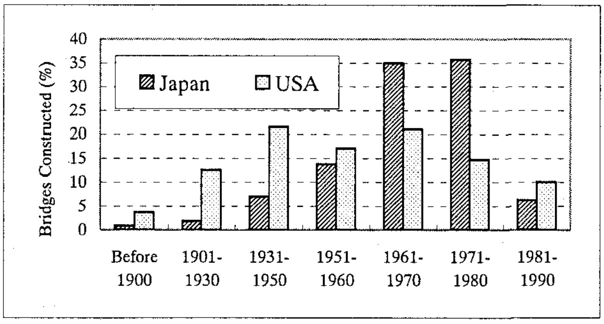

Figure 2. Comparison of Construction Period of Bridges in Japan and USA

There are various efforts of research on the lifecycle cost of bridges. Mohammadi et al. (1995) and Chang and Shinozuka (1996) focused on the development of conceptual models of bridge lifecycle cost. Frangopol et al. (1997) carried out a study on the lifecycle cost based on the deterioration of existing bridge structures. Liu and Itoh (1997) used optimization of maintenance strategies for lifecycle management of network level bridges. Efforts are also ongoing to reduce the lifecycle cost by the use of high performance steel (Wright 1998).

Besides the lifecycle cost, the environmental impact is being important in infrastructure management. Since environmental impact assessment of large projects is made mandatory in many countries, various research efforts are ongoing about the evaluations of environmental impact from infrastructure lifecycle. In a previous study, the global environmental impact has been considered as one factor for selecting the bridge type (Itoh et al 1996, Itoh et al. 2000b). Taking the energy consumption and CO_2 emissions from bridge construction activities as the indicators of global environmental impact, a system was developed to compare the candidate bridge types. Horvath and Hendrickson (1998) considered the comparison of a steel bridge and a reinforced concrete bridge with respect to the environmental impact from the bridge lifecycle. The toxic releases, hazardous wastes and local air pollutant emissions are considered as the environmental impact from the bridge construction and maintenance activities. In another study, high performance coating systems were developed to reduce various environmental hazards from bridge paints (Calzone 1998). Under the United Nations Framework Convention on Climate Change, Kyoto Protocol adopted in third conference of parties (COP3) has set numerical targets to reduce the greenhouse gases by 2012 (UNFCCC 1997). In Kyoto protocol, Japan has committed to reduce the greenhouse gas of 1990 level by 6% from 2008 to 2012. This needs all sectors to reduce the emissions of greenhouse gases including the construction sector. Various types of environmental effects are caused due to the bridge construction and maintenance activities like the generation of toxic materials, hazardous wastes, local air pollutant emissions and global environmental effects. Global warming is one major threat to the earth, which is caused by emissions of greenhouse gases. Therefore, this study focuses on the global environmental effects. Greenhouse gases like CO_2, CH_4, N_2O and so on are emitted during the different activities of bridge lifecycle. These emissions are the consequence of various activities that are dependent upon the consumption of natural resources and industrial activities consuming fossil fuels and energies. Since CO_2 occupies about 60% of total greenhouse gas, its emission is considered as the indicator of environmental impact in this study.

In this research, an approach is proposed to predetermine the CO_2 emissions and costs of bridges from the construction, maintenance and demolition stages based on an available system developed for the bridge type selection (Itoh et al. 1996, Itoh et al. 2000b). A case study on the lifecycle environmental impact and cost of two typical types of bridges is then carried out to identify the specific effects of each lifecycle stage, recycled material and others. Finally, this approach is applied for comparing the lifecycle CO_2 emissions as well as the lifecycle costs from both a conventional bridge and a minimum maintenance bridge proposed by PWRI to minimize the frequent maintenance requirements during the service lifetime of a bridge (PWRI 1997). Although the difficulties still prevail in predicting the lifecycle CO_2 emissions and costs of bridges with required accuracy at the time being, these values would be useful for a comparative analysis because the consistent methods are followed to evaluate various alternatives.

2. Basic Assumptions for Bridge Lifecycle Evaluation

2.1 Lifecycle Stages of Bridges

The lifecycle analysis has played an important role in the bridge management by considering all bridge lifecycle stages at the same time. Most of the previous researchers focused their research efforts onto the lifecycle cost analysis (Frangopol et al. 1997, Liu and Itoh 1997). Lifecycle analysis approach has also applied for the reliability analysis (Ellis et al. 1995) and the calculation on the environmental impact (Itoh et al 1999, Itoh et al 2000a). In this research, the bridge lifecycle represents the construction stage, the maintenance stage and the replacement stage only, which cover the major on-site activities and resource consumption.

2.1.1 Construction stage

Lifecycle evaluation at the construction stage needs the primary data of a bridge including its cross section data, span arrangement, structure 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.

2.1.2 Maintenance stage

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 the hearing with the practical bridge engineers, eight types of bridge components need more maintenance, which are the pavement, deck, painting, expansion joint, support, girders, guard fence, and pier (abutment), because of the structural deterioration due to the service and material aging. Among these eight components, however, the girder, guard fence and pier are usually damaged by some unpredicted events such as the earthquake and traffic accidents, and therefore it is difficult to determine the maintenance needs and the maintenance period of such a bridge component. In this research, only five bridge components are considered for the lifecycle evaluation, namely the pavement, deck, painting, expansion joint, and support. The maintenance periods (service lives) of these components are assumed to be 5~20, 15~30, 5~15, 5~20, and 20~30 years respectively by referring the hearing with the practical engineers and some publications such as Nishikawa 1994.

2.1.3 Replacement stage

There have been existing several common bridge replacement methodologies, such as (1) closing the traffic while replacing, (2) constructing a temporal bridge instead of the existing bridge under the replacement, and (3) closing a part of the bridge and keeping the other part for the 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 consumptions of materials and machinery of each replacement operation are essential. However, such data have not been summarized well so as to be able to be utilized for the further calculation. Therefore, the environmental impact and cost from the replacement stage in this research are assumed to be constants without considering the possible change due to the different method.

2.2 Life Time Estimation of Bridges

There are three types of service lives of a bridge or a bridge component, which are the structural service life, the functional service life and the economic service life (Nishikawa 1994). The structural service life is determined according to the deterioration of materials used in each bridge component, and the reduction of the entirety of a bridge. The functional service life of a bridge is the time from the construction to the replacement due to the lack of its function such as the increasing requirements on the loading capacity, the traffic volume, its length, width and height, and the seismic capacity. The economic service life of a bridge is determined according to the economic benefit to keep the bridge open for the service. In this research, the structural service life is taken consideration as the service life of a bridge without a specific definition to avoid the subjective effects onto the evaluation results.

Figure 3 shows the distribution of numbers of bridge replacement with the age (PWRI 1997). It is clear that two peaks are existing and their time periods are 15~30 and 40~60 respectively. By comparing the reasons in these two peaks, it can be noticed that the functional insufficiency in the first peak possesses a higher portion than it in the second peak, and the sum of the structural damage and loading-capacity insufficiency in the second peak is obviously larger than that in the first peak. Therefore, the structural service life of a bridge can be assumed to be 40~60 years and the service life of 60 years is used in the following of this paper.

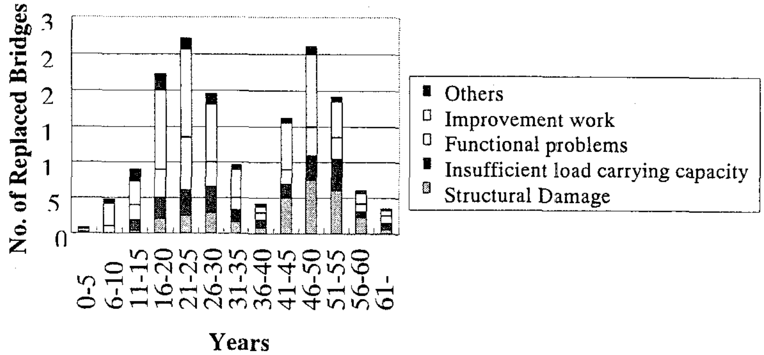

Figure 3. Distribution of Reasons for Bridge Replacement

3. Lifecycle Evaluation Methodology of Bridges

3.1 Calculation Methodology for Lifecycle Cost

Lifecycle cost is the total cost accrued during the life of a bridge. Various types of costs are incurred by the owning agencies and users during the service life of a bridge. User cost incurred due to the closure of a bridge for various reasons such as the maintenance and rehabilitation activities is a significant part of the lifecycle cost. However, in this research only the agency costs of bridges are considered for the lifecycle cost analysis. Mainly three types of costs are included in the lifecycle cost: construction cost, maintenance cost and demolition cost. The total lifecycle cost can be evaluated as:

$$LCC = \sum_{i=1}^{T_a}\sum_{j=1}^{N}(C_C(i,j)+C_M(i,j)+C_D(i,j))*(1+r)^{-i} \tag{1}$$

Where, LCC is the total lifecycle cost of a bridge for a given analysis period of T_a; $C_C(i,j)$ is the construction cost of the bridge component j at the year i; $C_M(i,j)$ is the maintenance cost of the bridge component j at the year i; $C_D(i,j)$ is the demolition cost of the bridge component j at the year i; and r is the average annual discount rate during the analysis period.

Several difficulties exist in predicting lifecycle cost with required accuracy. The construction and demolition costs can be estimated with fair degree of accuracy with several assumptions on the construction and demolition with help of manuals and databases. Since bridges last for several decades with various maintenance activities, the maintenance cost always becomes a significant part of the lifecycle cost. Estimation of maintenance cost needs proper understanding of maintenance strategies and historical databases of maintenance costs. However, such data are seldom available for the civil infrastructures, and the maintenance cost is normally assumed in the lifecycle cost calculations (FHWA 1998). The major maintenance activities and their frequencies in this study are adopted from previous literatures and interview with practicing bridge engineers. In such a condition of lack of data about lifecycle performances and effectiveness of maintenance strategies, it is very difficult to carry out the prediction of lifecycle cost accurately. Despite the difficulty in calculating the value of lifecycle cost accurately, lifecycle cost analysis can be useful in comparing several alternatives following the consistent method of evaluation. Further, if the lifecycle data will be gathered continuously, the present methodology can be improved to find more accurate value of the lifecycle cost in the future. Since the analysis period is relatively long, the selection of the discount rate is another difficult issue in the lifecycle cost analysis. Historically, the discount rate for the Bank of Japan has varied between 3.7-7.8% in 1883-1975 (Homer 1977). However, current annual discount rate of Japan is as low as 0.5% and even the 10 years' treasury bond has interest rate of only 0.85% (The Japan Times 1999). To be at the conservative side, a discount rate of 2% is taken as it is near to long-term discount rate of Japan.

3.2 Calculation Methodology for Lifecycle CO_2 Emission

The bridge lifecycle consumes the natural resources and energy in the form of construction materials and equipment. The construction materials used during the construction and maintenance can be accumulated to find the global environmental impact from bridges. The demolition stage also uses a lot of equipment for demolition activities and construction materials for temporary structures. The total lifecycle global environmental impact from the bridge lifecycle can be given by the following equation:

$$LEI = \sum_{i=1}^{T_a}\sum_{j=1}^{N}(I_C(i,j)+I_M(i,j)+I_D(i,j)) \tag{2}$$

where LEI = total lifecycle environmental impact; $I_C(i,j)$ is the environmental impact from the construction of the bridge component j at the year i; $I_M(i,j)$ is the environmental impact from the maintenance of the bridge component j at the year i; and $I_D(n)$ is the environmental impact from the demolition of the bridge component j at the year i.

The volume and weight of materials are calculated for a bridge lifecycle based on the design manuals and the interview with bridge engineers. Similarly, duration of construction equipment used in various construction, maintenance and demolition activities are found by the databases depicting past experiences and interview. The CO_2 emissions from per unit volume or weight are taken from the results studied by PWRI (1994) and JSCE (1997). The PWRI values are obtained by input-output analysis of Japan. The JSCE values are calculated with lifecycle assessment (LCA) method in which all processes are accounted for making a product. This LCA method is supplemented by input-output analysis. The differences of total CO_2 emission values using both PWRI and JSCE unit emission values are compared for the construction of two bridge types. The information of these two bridges is shown in Table 1 and the detail description is given in Section 4.1. Figure 4 shows that the PWRI unit emission values result in more total CO_2 emissions for two types of bridges, and the difference for PC bridges is small. This represents that the PWRI unit emission values for both steel and concrete are larger compared to the JSCE unit emission values. The two types of unit emission values for concrete are close compared to the unit emission values for steel. The CO_2 emissions are measured in ton of equivalent carbon (t-C). Since JSCE values are relatively new and are cross-checked with two methods, these values are used to calculate the lifecycle global 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.

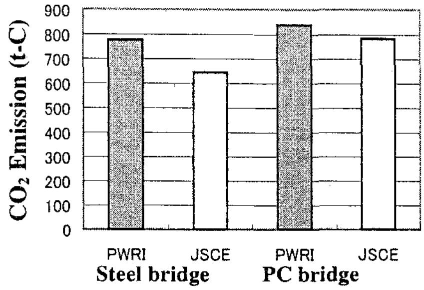

Figure 4. Comparison of CO_2 Emission from Unit Emission Values of JSCE and PWRI

4. A Case Study of Bridge Lifecycle Evaluation

4.1 Basic Data of Bridges

In order to identify the environmental impact characteristics in the construction, maintenance and replacement stages obtained from the developed system and to discover the possible revised approaches, a case study is carried out. Two typical superstructure types are considered in this case study, which are the steel simple non-composite I girder bridge and the PC simple pre-tensioned T girder bridge. The span arrangement for both bridges compared are of three spans with 33m+34m+33m. It is assumed that the bridge is located in Nagoya. The basic data are shown in Table 1.

Table 1. Bridge Data for the Case Study

Superstructure type	Type1: Steel simple non-composite I girder bridge Type 2: PC simple pre-tensioned T girder bridge
Bridge length	100m
Bridge width	17m
Spans	33m, 34m, 33m
Heights	1.9m, 2m, 1.9m
Number of main girders	9
Substructure type	Inverted T pier (abutment)
Foundation type	Reverse pile

4.2 Comparison of CO_2 Emission and Cost in Lifecycle Stages

Further comparison study on the CO_2 emissions and costs consumption from each lifecycle stage has been performed by considering three cases of deteriorating speeds (rapid, medium and slow) of each major bridge component as shown in Table 2. The basic data of bridges as same as shown above in Table 1. For the purpose of comparison, it is assumed that all bridge components have the same deteriorating speed. The unit in this table is year and the service life of a bridge is considered as 60 years old.

Table 2. Deteriorating Speed of Bridge Components (year)

	Case 1	**Case 2**	**Case 3**
Deteriorating speed	Slow	Medium	Rapid
Pavement maintenance	20	12	5
Re-painting	20	10	5
Deck maintenance	25	20	15
Deck replacement	50	40	30
Expansion joint replacement	20	12	5
Support replacement	30	25	20

Figures 5 and 6 represent the CO_2 emission and costs consumption from the three lifecycle stages of both a steel simple non-composite I girder bridge and a PC simple pre-tensioned T girder bridge, respectively. It can be concluded that a PC bridge contributes more CO_2 emissions than a steel bridge in each of three cases although its cost is relatively less.

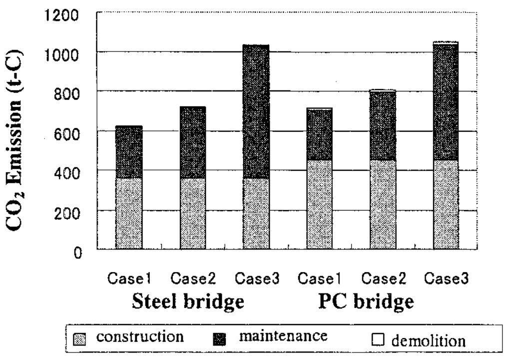

Figure 5. Composition of Lifecycle Environmental Impact

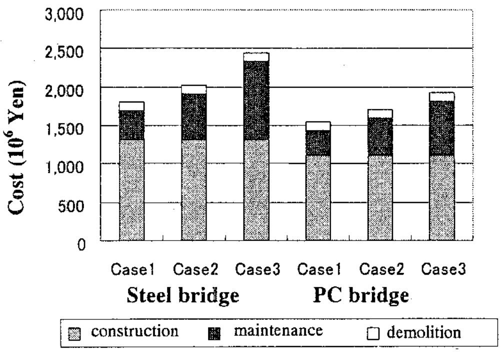

Figure 6. Comparison on Bridge Lifecycle Cost

4. 3 Comparison of CO_2 Emission from Bridge Components in Maintenance Stage

According to Figure 5, it can be noticed that the CO_2 emissions at the maintenance stage may be larger than it at the construction in the worst cases. Therefore, to reduce the lifecycle CO_2 emissions, the maintenance stage should be paid attention to as well as to the construction stage, and the further study on the CO_2 emission quantity from the maintenance of each bridge component becomes necessary. Table 3 represents the CO_2 emissions in t-C from each type of maintenance activities for the two bridges mentioned above. The CO_2 emission of a bridge component is obtained by summing the products of the consumed quantity of each material or machine needed for the maintenance activity and its unit value of CO_2 emission.

Table 3. CO_2 Emission per Maintenance Activity (t-C)

	Steel simple non-composite I girder bridge	**PC simple pre-tensioned T girder bridge**
Pavement	10.6	10.6
Painting	11.5	No painting
Deck maintenance	28.9	28.8
Deck replacement	117.9	121.5
Expansion joint	19.7	19.7
Support	13.7	34.2

Figures 7 and 8 show the CO_2 emission comparison from each type of maintenance activity of a steel bridge (a steel simple non-composite I girder bridge) and a PC bridge (a PC simple pre-tensioned T girder bridge) in three cases for a given service life of 60 years respectively. The descriptions of these three cases are given in Table 2. As the painting is not a key component of a PC bridge, it is not considered in the comparison shown in Figure 8. It can be noted from these two figures that the order of the CO_2 emissions from all maintenance activities may change due to the deterioration speeds of bridge components for both the steel bridges and the PC bridges.

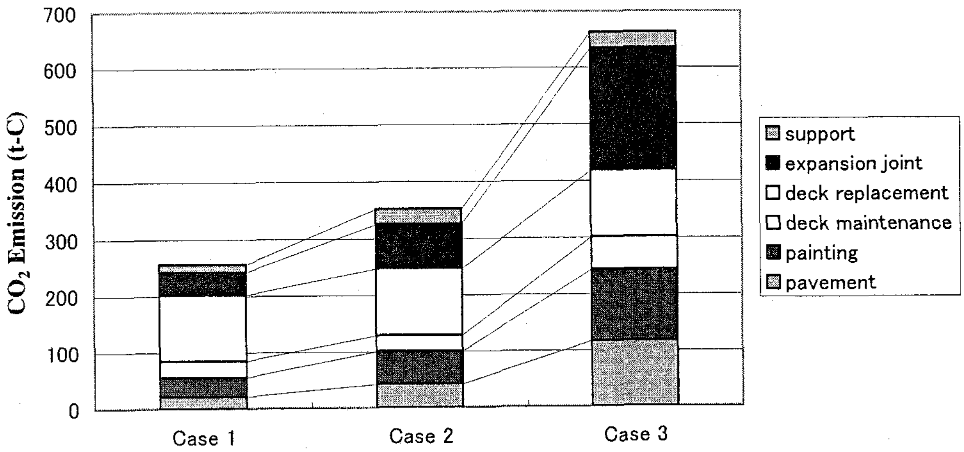

Figure 7. Environmental Impact due to Maintenance Activity of a Steel Bridge

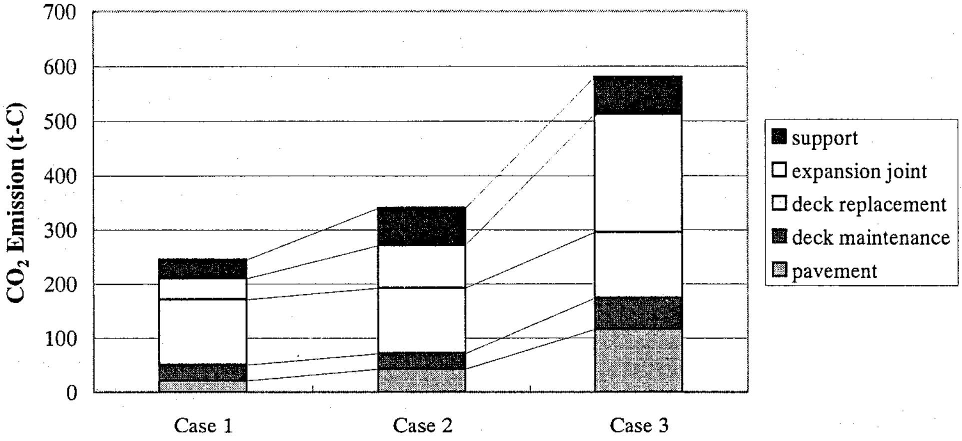

Figure 8. Environmental Impact due to Maintenance Activity of a PC Bridge

4.4 Effects of Recycled Materials

It has been widely noticed that recycling of construction materials is one efficient method for reducing the environmental impact as well as reducing the construction cost. As a majority of landfills is being of limited capacity and the construction waste holds a high portion of the solid waste, recycling will also be able to reduce the load to these landfills. The steel used in the superstructure can be recycled most efficiently with a ratio of more than 95% (PWRI 1994). Steel can usually be recycled by melting it in the electric arc furnace. This recycled steel can be used instead of virgin iron extracted from mines, which results in about 60% energy saving, and consequently, reduction in environmental impact (PWRI 1994). On the other hand, concrete can be recycled as aggregate for new concrete, as material for road base course, and so on (Bassan and Vittorio 1995). The environmental impact of concrete produced with recycled aggregate will be about 86% compared with conventional concrete (PWRI 1994).

As a high material quality is normally required to gain the confidence in safety for the construction of a large civil infrastructure such as bridges, in the present practice, the recycled materials are not used in Japan although the recycled materials such as steels in most cases can meet the requirement of the structural and functional capacities. However, with the development of recycling technology and the increasing burden onto the global and local environment, it is expected that more recycled materials will be used in the near future. Figures 9 and 10 present the effects of recycling onto the lifecycle environmental impact and cost respectively. The environmental impact and cost from the superstructure and substructure are separated during the calculation as only concrete substructures are considered. As shown in these figures, the use of recycled materials can decrease the environmental impact and cost to 10-20% and 2-5% respectively. Particularly the recycling of the steel of a bridge can result in higher percentages of decreases of environmental impact and cost compared to the recycling of the concrete. In addition, steel can be considered superior to concrete from the environmental point of view because steel can be recycled as steel, while concrete can be recycled only as aggregates. This means more limestone and other natural resources are still depleted even concrete is fully recycled.

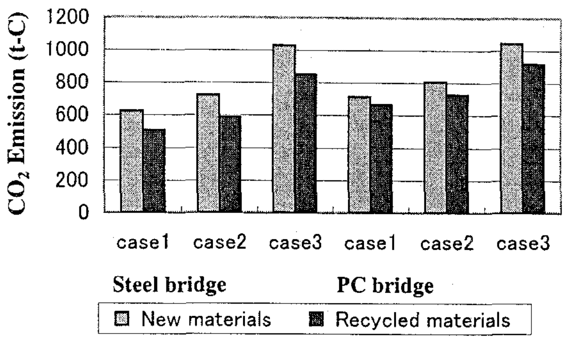

Figure 9. Effect of Recycling on Environmental Impact

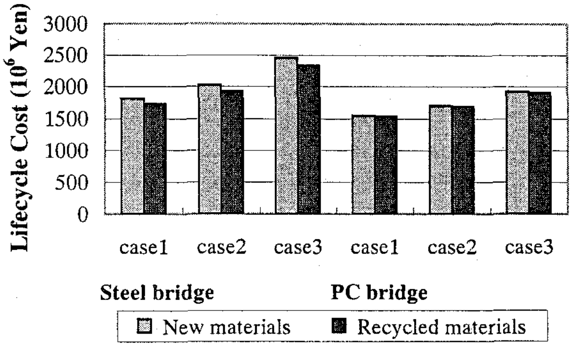

Figure 10. Effect of Recycling on Lifecycle Cost

5. Application Scenarios of Bridge Lifecycle Evaluation

5.1 Minimum Maintenance Bridges

5.1.1 Requirements of improved bridge life

A minimum maintenance bridge can be defined as a bridge designed, constructed and maintained with the objective of a practically permanent bridge requiring minimum maintenance actions. Such a bridge is conceptualized by making critical components of the bridge more durable and of less frequent maintenance requirements.

A permanent bridge having an infinite life without any maintenance is preferred so that there will be no maintenance cost in future. However, such a bridge is impossible in practice as all materials deteriorate gradually when exposed to the environment and traffic. Fatigue of materials due to repeated applications of wheel loads restricts the bridge life to a finite length. A practical solution will be to aim the bridge longevity with high initial quality and minimum maintenance activities. At present, fatigue life of 200 years is considered very long even though it is thought to be possible by careful technical considerations. If the average bridge life is considered as 200 years from the viewpoint of fatigue, the probable range of bridge life can be thought in the order of 100 to 400 years. This range is quite long (more than 3 folds) in comparison to average bridge life of 60 years at present. Therefore, 200 years as an average life of a bridge can be considered as a permanent bridge. Improvement in the design methods of bridge components is the basic step in achieving this target. Well-coordinated design, construction and maintenance are also needed to sustain the bridge longer.

5.1.2 Main technical development for minimum maintenance bridges

By the observation of causes of bridge replacement, the prevention of corrosion of steel and damage of deck slabs is necessary to realize a long life bridge with minimum maintenance. This subsection will describe the proposed strategies to overcome the corrosion of steel and damage of deck slabs with some available technologies and newly developed methods.

The corrosion of steel is the most severe problem in steel bridges. Frequent coating is needed in case of ordinary painting to prevent the corrosion. Two principles can be adopted as countermeasures for preventing corrosion of steel with minimum coating. The first principle is the use of steel that do not corrode and the second is application of coating that lasts longer. Rust-proof steel materials such as stainless steel or clad steel with titanium can be used as the cover to delay the rust action of the steel materials of a bridge. Titanium cover is used in steel bridge piers in Japan on the Trans-Tokyo Bay Highway, performance of which is still being monitored. Weathering steel was introduced in highway bridges from late 1960s (Tonias 1995). Weathering steel can prevent rusting effectively without painting if there are no airborne chloride ions in the surroundings. High performance weathering steel is under development stage to avoid or minimize painting activity, and thereby to reduce the lifecycle cost (Wright 1998). Various types of heavy paintings have been developed to cut the supply of oxygen and water completely by covering the steel surface. The problem with this technique of covering the surface by painting arises around the critical parts such as edges, bolts and the steel surface with some defects (Nishikawa 1997). It will be difficult to maintain uniform paint thickness in such areas. This is why the use of paintings to cover the surface may not be considered a good technique of corrosion prevention. This disadvantage of painting can be avoided by adopting electroplating techniques such as zinc galvanization. In this case, corrosion is prevented by a zinc surface with high tendency of ionization as a sacrificial metal. Zinc-galvanized pylon towers are expected to have a durability of 50-60 years even when they are exposed to the direct effect of rainwater and sun. However, in case of a bridge, the galvanized part of the bridge can be protected by the direct effect of rainwater and sun by adopting deck type bridges. In such protected environment, the life of zinc coating can be expected to be longer. Several galvanized bridges in Japan are in good condition without any sign of deterioration after more than 30 years since construction.

For making the deck slab durable, the damage mechanism needs to be understood to propose an appropriate design method. The wheel-running testing machines have been used in the laboratory of PWRI to simulate the damage patterns of RC deck slabs of bridges in Japan (Nishikawa 1997). It was found that the cracks first starts through slab by bending action under the moving wheel load and finally breaks down by punching shear. The damage propagation of the deck slab can be prevented by careful design. Shrinkage cracking can be prevented by proper curing or use of expansive concrete. Pre-stressing in longitudinal direction can prevent the damage process initiated by wheel applications. Most RC slabs designed by current design code have failed after 10 years due to such fatigue phenomenon. Fatigue life of pre-stressed concrete slab is found to be several times that of RC slabs. The fatigue life can be made longer by adopting a PC deck slab with a double of the cost of a RC deck slab. Corrosion of reinforcement is another problem in deck slabs that is usually caused by the application of deicing salts (Frangopol et al. 1997). Provision of coated reinforcements in RC deck slabs can increase the durability of deck slab by reducing the chance of corrosion of reinforcement.

5.1.3 Additional treatments in minimum maintenance bridges

In addition to the above two main techniques, further considerations are necessary to make other bridge components more durable to conceptualize the minimum maintenance bridges. From the viewpoint of durability, the deck-type bridges can be preferred over through type bridges. The deck type bridges have majority of bridge components below the deck slab that acts as the roof to prevent rainwater and ultraviolet rays from the sun. Using the girders with smaller number of joints or without joints and minimizing the length of the welding, increased stiffness can be obtained. The increased stiffness provides improvement in durability to the girder. If the bridge is made continuous over several spans, the number of joints will also reduce so that leakage of water to the bridge parts can be prevented. A bridge can be made continuous over several spans by the adoption of supports like seismic base isolated support in Japan considering frequent earthquakes. Using elastic support like rubber bearings, the replacement cycle can be increased. Fatigue problem at the edge of the girder (Hanshin 1992) can be avoided by the use of rubber supports. Rubber supports are being popular in Japan after Great Hanshin Earthquake of 1995. Among the bridge components, wearing surface needs most frequent replacement. Improved asphalt wearing surface can be used to increase the cycle of pavement repair and replacement. By preventing the soaking of water on the bridge surface, the durability of pavement as well as deck slab can be increased. The major consideration should be given to avoid stagnant water by providing slope to the pavement. By constructing curb around the road surface, drain water can be discharged properly. It can prevent the deck slab, girder and substructure from the corrosion due to the leakage of drain water. The structure of expansion joints can be devised so that it can be easily replaced. It can be made possible by fixing the joint with the deck with strong nuts. Durable types of expansion joints are proposed as conventional joints need frequent replacement. Guardrails should also be easily replaceable. The maintenance operation can be made simple by connecting guardrail structures with strong nuts so that it can be easily replaced.

5. 2 Comparison between Conventional and Minimum Maintenance Bridges

5.2.1 Bridge models for various conditions of traffic and environment

The bridge service life and maintenance interval mainly depend upon the traffic condition and surrounding environment such as the climate. In order to study the effect of making the bridge service life and the maintenance interval for bridge components longer, different scenarios of traffic conditions are considered. Bridges in three locations are considered to explore the effect of different environment and traffic level: (1) Bridges in the mountain area: The traffic is light and the surrounding environment is not severe for corrosion in the mountain area. Unpainted weathering steel is a good candidate for such environment. The RC slab with coated reinforcement can be provided as a durable deck. (2) Bridges in the coastal area: The traffic level is normal but the surrounding environment is severe for corrosion in the coastal area. The RC slab with coated reinforcement can be provided for the prevention of decay of reinforcement bars due to chloride attack. (3) Bridges located in the urban area: The traffic is heavy and the surrounding environment is normal for corrosion in the urban area. When the bridge is adjacent to business street or residential area, special care should be given to landscape during the selection of paint materials to keep the harmony with the surrounding. Zinc galvanization with appropriate color can be applied. The PC deck can be provided to cope with the effect of heavy traffic. The difference between the minimum maintenance bridge and conventional bridge is summarized in Tables 4, 5 and 6 for bridges at mountain, coastal and urban area respectively.

Table 4. Bridge Models for Mountain Area (year)

Items	Minimum Maintenance Bridge		Conventional Bridge	
	Sub-component	**Life**	**Sub-component**	**Life**
Replacement cycle		200		60
Initial Painting	Weathering steel	200	Phthalic resin paint	15
Repainting	-	-	Phthalic resin paint	15
Deck type	RC deck (reinforcement)	200	RC deck	60
Deck rehabilitation	Patch repair	40	Patch rehabilitation	30
Deck replacement	-	-	-	-
Bearing	Rubber bearing	100	Steel bearing	30
Expansion joint	Durable expansion joint	40	Normal joint	20
Wearing course	Improved asphalt	20	Normal asphalt	15

Table 5. Bridge Models for Coastal Area

Items	Minimum Maintenance Bridge		Conventional Bridge	
	Sub-component	**Life**	**Sub-component**	**Life**
Replacement cycle		200		60
Initial Painting	Zinc galvanizing & paint	100	Polyurethane paint	20
Repainting	-	50	Polyurethane paint	20
Deck type	RC deck (reinforcement)	200	RC deck	40
Deck rehabilitation	Patch repair	40	Patch rehabilitation	20
Deck replacement	-	-	Grating deck (up to replacement)	40
Bearing	Rubber bearing	100	Steel bearing	30
Expansion joint	Durable expansion joint	40	Normal joint	10
Wearing course	Improved asphalt	15	Normal asphalt	10

Table 6. Bridge Models for Urban Area

Items	Minimum Maintenance Bridge		Conventional Bridge	
	Sub-component	**Life**	**Sub-component**	**Life**
Replacement cycle		200		60
Initial Painting	Zinc galvanization	130	Chloride rubber paint	15
Repainting	Spaying of zinc	70	Chloride rubber paint	15
Deck type	PC deck	200	RC deck	40
Deck rehabilitation	Partial rehabilitation	40	Partial rehabilitation	20
Deck replacement	-	-	Grating deck (up to replacement)	40
Bearing	Rubber bearing	100	Steel bearing	30
Expansion joint	Durable expansion joint	20	Normal joint	10
Wearing course	Improved asphalt	15	Normal asphalt	15

5.2.2 Comparison of lifecycle cost and global environmental impact for bridge models

Further comparison of a conventional bridge and a proposed minimum maintenance bridge with respect to the lifecycle cost and global environmental impact is carried out. Calculations are carried out for a bridge length of 30 m, details of which are shown in Table 7. Since all bridges can have the similar substructure, only cost and CO_2 emission from the superstructure are considered. The replacement cost of a conventional bridge at the end of each lifecycle of 60 years, including the demolition cost and re-construction cost, is assumed to be three times of the initial construction cost of a new bridge (Nishikawa et al. 1996). To compare the cost performance, the initial cost of a conventional bridge of each category is given a value of unity. The environmental impact from construction stage of a conventional bridge is assigned a value of unity. The cost and environmental impact values are calculated for every 5 years of an interval. The relative index for the cost is calculated for every 5 years by $C(n)/C_i(0)$. The symbol $C(n)$ is the cumulative cost of the *n-th* year, and $C_i(0)$ is the initial cost of a conventional bridge. The relative index for the environmental impact is also calculated for every 5 years by $I(n)/I_i(0)$. The symbol $I(n)$ is the cumulative environmental impact value for the *n-th* year; and $I_i(0)$ is the environmental impact from the construction of a conventional bridge.

Table 7. Details of Bridge for Comparison

Superstructure type	Steel Simple Non-Composite I-Girder Bridge
Bridge length (m)	30.7
Girder length (m)	30.6
Clear span (m)	30.0
Overall width (m)	11.5
Effective width (m)	10.5
Width of driveway (m)	7.5
Width of pedestrian walk (m)	3.0
Number of girders	5

Figures 11 to 13 show the relative indices of cost and environmental impact from a conventional bridge and a minimum maintenance bridge for three scenarios located in the mountain area, coastal area and urban area respectively. In these figures the symbols CB and MMB represent a conventional bridge and a minimum maintenance bridge.

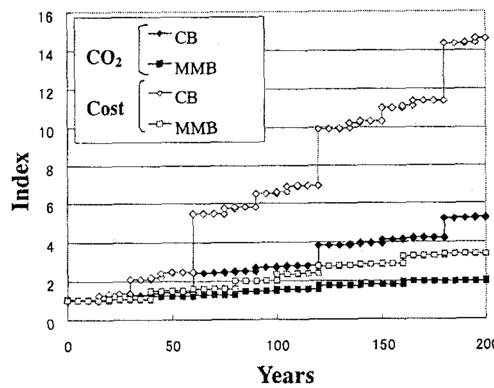

Figure 11. Comparison at Mountain Area

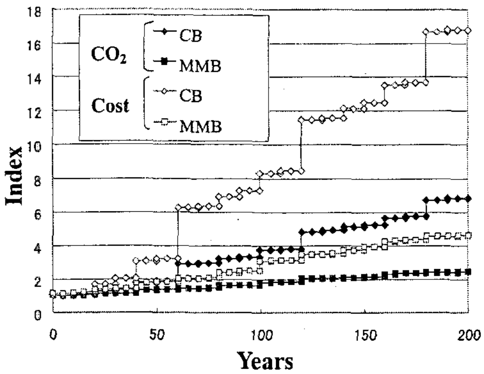

Figure 12. Comparison at Coastal area

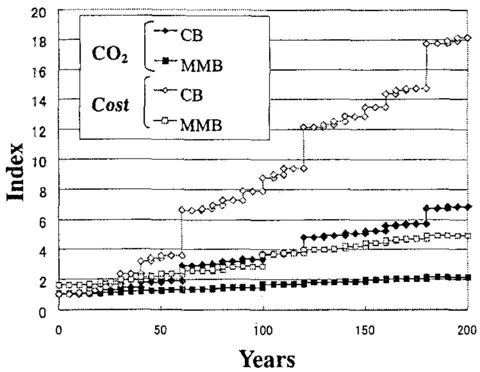

Figure 13. Comparison at Urban area

For the bridges in the mountain area as shown in Figure 11, the relative index of the lifecycle cost for a conventional bridge at the end of 200 years is about 4.3 times of the relative index value for a minimum maintenance bridge. The relative index of the environmental impact for a conventional bridge at the end of 200 years is about 2.6 times of the relative index for the minimum maintenance bridge. This means that the minimum maintenance bridge causes less environmental impact and needs less cost for a given periods of 200 years compared to a conventional bridge. The relative index for cost as well as environmental impact increases abruptly during the end of replacement cycle for the conventional bridge. Therefore the main reason for higher lifecycle cost and environmental impact of the conventional bridges is due to frequent replacement cycle. Similar conclusions can be stated for the bridges located at the coastal area and urban area as shown in Figures 12 and 13.

6. Conclusions

In this paper, a lifecycle environmental impact and cost evaluation approach has been proposed based on a previous research for the construction stage only. This proposed approach was further applied for determining the lifecycle environmental impact of a new type of bridges that were designed to minimize the bridge lifecycle cost. Following conclusions can be stated from this research:

(1) The lifecycle environmental impact and cost of a bridge could be determined by utilizing and strengthening an existing bridge type selection system.

(2) A case study on the lifecycle environmental impact and cost of two typical types of bridges made it clear to identify the portions from each lifecycle stage and each maintenance activity, and the effects of recycling. A PC bridge contributes more CO_2 emissions than a steel bridge in each set of three deterioration speeds of bridge components although its cost is relatively less. The order of the CO_2 emissions from all maintenance activities may change due to the deterioration speeds of bridge components for both the steel bridges and the PC bridges. The use of recycled materials can decrease the lifecycle environmental impact of about 10% for a PC bridge and 20% for a steel bridge respectively, and the lifecycle cost of about 2-5%.

(3) The minimum maintenance bridge proposed by the Public Works Research Institute could drastically reduce the lifecycle environmental impact of a bridge as well as its lifecycle cost. For example, in case of a bridge constructed in the mountain area, the lifecycle cost of a conventional bridge at the end of 200 years is about 4.3 times of the cost of a minimum maintenance bridge. Furthermore, the CO_2 emission of a conventional bridge at the end of 200 years is about 2.6 times of the CO_2 emission of a minimum maintenance bridge.

Because of the insufficiency of data, simplifications and assumptions were adopted in this research for the bridge lifecycle evaluation. The numerical results could become more accurate with the accumulation of the necessary data. The authors would like to thank the Bridge Office of Nagoya City Civil Bureau for providing data and knowledge during the hearing. The partial financial support of the Ministry of Education, Science, Sports and Culture in Japan as the Foundation of Science (No. 11555124) is gratefully acknowledged.

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