On the Necessity and Feasibility of Extending the Service Life of Existing Buildings

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Abstract: In order to continue to give play to the investment benefit of existing buildings, relevant technical specifications were studied and value analysis and technical feasibility justified for extending the service life of existing buildings on the basis of systemic analysis and assessment of the full life cycle of buildings and their initial construction cost, service maintenance cost, demolishing recovery cost, residue treatment cost and the energy consumption and CO_2 discharge, with the conclusion that this practice is necessary and feasible. For the subsequent work, research orientation and suggestions on improving the associated laws and regulations and technical standards were proposed.

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1. Introduction

Buildings are characterized by high construction cost, long construction cycle, high energy consumption and long investment return period. During China's reform and opening up, the rapid development of the construction industry has driven the development of planning, design, survey, construction, supervision, consulting, cement, steel and other building materials and related machinery manufacturing industry chains, greatly improving the overall national strength and people's living standards, and it has become an important pillar industry of the national economy.

According to the 2005 Statistical Bulletin of the General Survey of Cities and Towns, by the end of 2005, the building area of urban houses in China's cities and towns was 16.451 billion m^2, after 2006, it would grow by more than 1 billion m^2 a year, and about 4.676 billion m^2 was built before 1985. A large number of existing buildings are approaching their designed service life (50 years). If the service life of existing buildings is extended, the great social and economic benefits of infrastructure investment can continue to be brought into play. This paper will systematically discuss and study the necessity and feasibility of extending the service life of existing buildings.

2. Full life cycle cost analysis of buildings

The full life cycle of a building refers to the full life cycle process of a construction project from its conceiving to demolition. The full life cycle cost of a building refers to the monetary cost discounted from the total cost of construction, operation, maintenance, demolition and recovery in the whole life cycle of a construction project, generally including the initial construction cost and future cost [1]. According to a document from the US Department of Energy, the initial construction cost accounts for 34%~43% of the lifetime cost (7%~15% as project initial period cost, and 27%~28% as the construction cost), and the future cost accounts for 60% ~ 66% [2].

2.1 Initial construction period and cost

2.1.1 Initial construction period

The initial construction period can be divided into the following four phases:

1) Construction project decision-making phase: including planning the proposed project, putting

forward the project proposal, justification of feasibility study report, obtaining the land use right after siting for land expropriation or through auction, bidding, and listing, and making the investment decisions and applying for construction based on the maximum full life cycle return or minimum cost. In developed cities, land cost accounts for more than 50% of the total construction cost, and in first-tier cities, it can be as high as over 6000 yuan /m^2.

2) Design phase: it is an important step to turn the construction project from a plan to the construction blueprint, and provide the process service for the project implementation. The design quality will be highly related to the construction cost, service and maintenance cost and safe operation of the project. The main work content is to complete the planning, survey, design and to obtain approval for the environmental impact assessment, anti-seismic, fire protection and energy saving facilities of the project.

3) Tendering phase: the main work is to select contractors, effectively control the project cost, invite bids in the principles of openness, impartiality and fairness, respectively assess the technical and commercial parts of the bid, and select the contractor with the best technical scheme and lowest construction cost for the work.

4) Construction implementation phase: mainly covering the construction and installation works, equipment and materials procurement, project supervision, cost consulting, completion acceptance, completion settlement, financial final accounting and transfer of assets, and handover for use. The construction and installation works is the key part determining the project quality and construction schedule. The state has set schedule quota for construction projects of different scale and complexity, and most owner entities set the construction schedule target with reference to the schedule quota and in conjunction with the actual conditions. It is mostly 2 or 3 years for ordinary high-rise buildings.

2.1.2 Initial construction period cost

The initial construction cost consists of construction and installation cost, equipment purchasing cost, land expropriation cost and other costs. The construction and installation cost consists of direct engineering fees such as labor fee, materials, and cost of using machinery, and indirect construction fee such as construction measures and construction management fee, as well as specified charges and taxes; equipment purchasing cost includes the equipment factory price and purchasing and freight; other costs include the initial expenses of the project (including feasibility study justification, environmental protection, fire protection and energy saving assessment and planning submission and review fee), expenses on urban infrastructure, project overheads, technical services (including survey, design, supervision and testing expenses), and bank interest. For this part, the statistics for construction and installation works has become fairly mature, the tendering control price can be prepared on the basis of the project consumption quota set in the state regulations and by competent authorities and equipment and material information prices, and in conjunction with the market situation, market competition can be carried out through bidding, to determine the contract price, and to finally determine the actual total construction price of the project through final accounting for completion.

The construction and installation cost is about 1000~1500 yuan/m^2 for ordinary small high-rise apartment buildings, and about 1500~2000 yuan/m^2 for ordinary high-rise apartment buildings. The higher grade of buildings, the higher cost. In recent years in coastal regions, with the development of economy, the construction grade and standards of buildings have kept on rising, accordingly, the construction cost and energy consumption level have also increased.

The market price of ordinary high-rise commodity houses has reached 50,000~100,000 yuan/m^2 or even higher in first-tier cities, and about 20,000~50,000 yuan/m^2 in the second tier cities, but the purchasing expenses of owners really spent on the actual total cost of the buildings (excluding the land cost, sales cost, corruption cost and unreasonable profit) is only about 10000 yuan/m^2.

2.2 Operation and maintenance period and cost

2.2.1 Operation and maintenance period

Buildings under normal design, normal construction and normal use and maintenance have good durability, fatigue resistance and environmental erosion resistance. It is specified in the Unified Standard for Reliability Design of Building Structure that, the design service period is 50 years for ordinary houses, and 100 years for monumental buildings and particularly important architectural structures [3]. However, the actual service life of many buildings is longer than the design service life. For example, ancient buildings with historical and cultural value or commemorative significance at home and abroad have stood for hundreds of years under protection due to proper use and timely maintenance and repair.

2.2.2 Cost in operation and maintenance period

Cost in the operation and maintenance period is also known as the future cost, being the cost incurred from the start of operation of the building and its ancillary facilities up to their demolition. With reference to the LCC analysis data [2] of a research institution on an office building cluster in New York, the ratio of the building operation and maintenance cost to its initial construction cost is 50.4: 49.6.

The building operation cost refers to the cost of water, electricity, gas and property management needed for daily life and production. For civil buildings, this part of the cost is the consumption necessary for the daily life of the users, which is a controllable dynamic cost, and its amount is determined by the consumption level of the users.

Maintenance cost refers to the maintenance and repair cost in the operation of the building and ancillary facilities, mainly including the normal maintenance cost of the power distribution system, water supply and drainage system, air conditioning and ventilation system, fire protection system, safety monitoring system, elevators, and decoration of the building. In general, the maintenance plans and budgets can be made according to the damage to buildings caused by use and the environment, and they can be included into the annual planning cost.

This cost varies greatly due to the differences in building scale, construction standards, building facilities and the use intensity of the owners. For example, for multi-storey residential areas, the maintenance cost is only 2 to 5 yuan /m^2·month, while for high-rise and high-grade residential areas, it is about 10 to 20 yuan /m^2·month.

2.3 Demolishing and recovery period and cost

2.3.1 Demolishing and recovery period

The service life of the building terminates when the building is no longer worth maintenance and retaining. The residue of old building or building ground still with the use value shall be demolished and recovered. For large buildings such as high-rise buildings and super high-rise buildings, the cycle and cost of the disposal of building residues must be considered in the demolition and recovery process, which is expected to take half a year or longer time to complete. Due to the high demolition cost, the demolition and recovery is generally started after the completion of the design of the new project on the original site, and is included as the initial engineering cost of the new project.

2.3.2 Demolishing and recovery cost

At present, China has not reached the peak period of building demolition and recovery, and the original low cost and high pollution demolition and recovery method is adopted in most cases. Generally, the construction slag is directly buried without any treatment after the demolition of the building by using construction machinery (multi-storey) or blasting (high-rise). It accounts for about 98% in Shenzhen, and about 2% with waste metals and waste concrete preliminarily sorted out; in Beijing, 20~30 construction rubbish disposal grounds are set up every year; in Shanghai, only about 20% of construction rubbish can be reused [4]. Just imagine that now, in the first and second tier cities, there are forests of high buildings, but after 40~50 years when the life of these concrete forests ends, such primitive "low cost" demolition and recovery method will not be able to digest large amount of construction rubbish at all, so they will surely exceed the carrying capacity of the environment and become the hidden danger of urban construction. Even if the advanced treatment method of current developed countries is adopted, it is very difficult to demolish the basement and foundation of high-rise buildings, and its cost is not lower than the construction cost. Also, to reuse the concrete waste residue as aggregate, the cost is higher than the present natural stone, but the quality is lower than the natural stone; if concrete waste residue is used as recycled cement, its cost is higher than that of cement made from natural stone, but its quality is lower than that of natural stone cement. In general, the demolition of concrete high buildings will not be lower than the initial construction cost, to take back the construction ground. Only with high-rise building of steel structure, the demolition and recovery cost is negative, at about 2%-10% of the construction cost, but the maintenance cost is high.

3. Full life cycle social cost assessment of buildings

According to estimates from the European Institute of Architects, the energy consumption of a building in the whole process accounts for 50% of the total energy consumption. Buildings contribute 50 percent of air pollution, 42 percent of greenhouse gas effects, 50 percent of water pollution, 48 percent of solid waste and 50 percent of fluorochloride [5]. Qiu Baoxing, former vice minister of the Ministry of Construction of China, introduced at the 2006 National Conference on Building Science and Technology that in 2006, China had a building area of more than 40 billion m^2 in urban and rural areas, about 95% of which were high energy-consuming buildings. Building energy consumption has accounted for 27.5% of total end energy consumption. It is estimated that by 2020, the country's urban and rural floor space will be added by more than 30 billion m^2. Without effective energy-saving measures, 120 million kWh of electricity and 410 million tons of coal equiv. will be consumed each year by buildings, nearly three times the present level in the country [6]. It is bound to cause serious pollution and the rise of atmospheric CO_2 concentration. Once the environmental limit is exceeded, the ecological environment will be damaged and social and economic development will be affected.

3.1 Construction energy consumption and carbon dioxide discharge

Construction energy consumption includes that in construction process, that by construction waste and that by building materials:

The comprehensive construction energy consumption from earthwork excavation to completion of slag removal is about 1328000KJ/m^2 [7], or 45 Kg/m^2 when converted at 29307 KJ per kg of coal equiv.

The construction wastes generated in the construction process, such as concrete blocks, bricks, stone block, stone debris, sand, waste soil, waste wood, waste metal and waste pipeline, are estimated to be about 40~150Kg/m^2 according to relevant domestic data [8], or 60~90 Kg/m^2 by average. It means average consumption of coal equiv. at 2.0 Kg/m^2 when converted as about 2.0t of coal equiv. for 100.0t of construction wastes.

The main building materials include cement, sand, stone and steel, aluminum, glass, etc., all being high energy-consuming materials, among them:

(1) Cement is a basic and traditional industry in China, and a high-energy-consuming industry. According to relevant data, the energy consumption of cement accounts for about 75% of the total energy consumption of the building materials industry in China, and the coal consumption accounts for about 15% of the total coal consumption in China. Now the unit comprehensive energy consumption in the cement industry is 105-118kg/t of coal equiv., or 112kg /t by average.

(2) The national average level of energy consumption for metallurgical steelmaking is about 740 kg/t coal equiv.; and the average level of steel rolling is about 215 kg/t.

(3) The comprehensive power consumption of electrolytic aluminum ingots per unit product is about 14000kWh/t, equivalent to 4200kg /t of coal equiv.

(4) The domestic advanced level of glass energy consumption is 6500KJ/kg; equivalent to power consumption of 18kWh/kg, and 56kg/kg of coal equiv.

For ordinary high-rise residential buildings, the cement consumption is about 150kg/m^2, and the steel consumption is about 80Kg/m^2. The theoretical value of coal equiv. converted into 1Kwh power is 122.9kg, and by taking into account power generation efficiency, 1Kwh power is equivalent to 360kg of coal equiv. Rough estimation shows that the energy consumption per square meter of building is145kg of coal equiv.

Also according to the rough estimation of 1kWh power equal to about 785km of carbon dioxide discharge, the carbon dioxide discharge in construction of ordinary high-rise buildings is about 319kg/m^2.

3.2 Energy consumption and carbon dioxide discharge in operation and maintenance

The energy consumption of building operation includes the energy consumption of lighting, ventilation, heating, air conditioning, elevator and various household appliances, the energy consumption of household wastes and the energy consumption of maintenance and repair when people use the buildings. Such energy is dynamically consumed by people in using the buildings. Due to the large difference in people's demand for the quality of life, the energy efficiency and energy-saving functions of various buildings also vary greatly. With the growth of people's economic income and the demand for the quality of life, energy consumption (air conditioning, ventilation, air purifier, etc.) to improve indoor and outdoor air quality will increase year by year. Air conditioning energy consumption accounts for over 1/2 of building operation energy consumption.

The amount of household garbage is about 0.5~1.0kg/person·day, and the energy consumption is about 1.42kg/t coal equiv. for landfill treatment, about 5.92Kg/t coal equiv. for composting treatment, and the comprehensive energy consumption is about 0.4kg/t coal equiv. for waste-to-energy treatment [10].

The maintenance energy consumption is relatively low, so there is no calculation and statistical data available about the maintenance energy consumption. Strengthened maintenance is usually conducive to energy saving, so it is tentatively ignored.

Carbon dioxide is discharged in the daily life of people, and this discharge (kg) is equal to kWh of electricity consumed multiplied by 0.785.

In household natural gas, the carbon dioxide discharge (kg) is equal to the cu.m. of natural gas used multiplied by 0.19.

In household running water, the carbon dioxide discharge (kg) is equal to the cu.m. of running water used multiplied by 0.91.

In traveling by car, the carbon dioxide discharge (kg) is equal to the oil consumed multiplied by 2.7.

3. Energy consumption and carbon dioxide discharge in demolition and recovery

The energy consumption in demolition and recovery includes that of demolition and in disposal of construction wastes. As estimated with relevant data, the demolition energy consumption is about 90% of the construction energy consumption in China [7]. Old buildings demolished will produce 700~1200kg of construction wastes per square meter [11]. Converted at digesting 1.0t of construction wastes to save 20.0kg of coal equiv., the energy consumed to demolish every square meter of ordinary high-rise building is about 20kg of coal equiv.

Converted at 22kg of carbon dioxide discharge per kg of coal equiv., the discharge in demolition of ordinary high-rise building is about 440kg/m^2.

4. Necessity and feasibility of extending the service life of existing buildings

4.1 Interpretation of relevant technical specifications and standards

4.1.1 Design service life

The Unified Standard for Reliability Design of Building Structures [1] clearly states that the design service life is a service period specified by the design, during which the structure or structural components can achieve the predetermined service function under normal service and maintenance without major repair; all design, construction, materials and equipment are aimed at achieving this goal, and this is the minimum safe service period target required for all buildings. For ordinary buildings, the design service life is 50 years.

4.1.2 Limit service life

1) Interpretation of design safety coefficient

The design method of limit state based on probability theory is adopted for building structural design in China. The Code for design of building foundations specifies that the standard value of pile foundation bearing capacity shall be 0.5 times the ultimate bearing capacity [12].

The loads used in structural design are based on the combination of the most unfavorable conditions and are the product of the standard values of loads and partial coefficients. It is specified in Load code for design of building structures [13] that the partial coefficient for constant load is 1.2 (adjusted to 1.3 in the 2019 version of the standard), and that for live load is 1.4 (adjusted to 1.5 in the new version); in Code for design of concrete structures, the design value of concrete compression strength is less than 0.5 times the ultimate compression strength value, and the ratio of design strength to ultimate strength standard value of ordinary reinforcement is 1:1.5 [14], by combining the two and multiplying with the load coefficient, the design bearing capacity standard value of building structure is below 0.5 times the actual ultimate bearing capacity, that is, under normal design conditions, the design safety margin of building structure is over 2.0, consistent with the safety margin of the foundation.

2) Interpretation of construction safety coefficient

Relevant construction standard also set the safety guarantee requirement on construction quality, and the Quality acceptance code for concrete works stipulates that the actual compression strength of concrete works shall be no less than 1.10 times the design strength [15]. Under normal construction conditions, the construction safety margin is 1.1.

3) Interpretation of anti-seismic safety coefficient

After the Tangshan Earthquake in 1976 in China, the Standard for classification of seismic protection of building constructions set the protection target of “not falling in big earthquake” that anti-seismic protection shall be provided from degree 6 and be 1 degree higher than the fortification intensity. The anti-seismic protection standard after 1989 further specified the protection target of “not falling in big earthquake” for all buildings. It is specified in the Code for seismic design of buildings [16] that all houses and buildings designed to the standard shall meet the protection target “not damaged in frequent earthquakes, repairable after fortification intensity earthquake and not falling in a rare earthquake”. Here, the frequent earthquakes, fortification intensity earthquake and rare earthquake are based on basic earthquake intensity zoning or ground motion parameter zoning, respectively being earthquakes with probability over 60%, 10% and 2~3% in 50 years, or earthquakes with return period of respectively 50, 475 and 1600~2400 years.

According to the Code for seismic design of buildings, the partial factor, seismic adjustment coefficient and the seismic augmentation coefficient are calculated for the seismic actions adopted in the seismic design, and the comprehensive seismic safety coefficient is above 2.0 [17].

Based on interpretation of the comprehensive analysis of the design safety coefficient, construction safety coefficient and seismic safety coefficient within the design service life, it can be concluded that the ultimate service life under normal design, normal construction and normal service maintenance is the product of the design service life, the design safety coefficient (2.0) and the construction safety coefficient (1.1). The ultimate service life of ordinary buildings should be 110 years.

4.2 Reasonable service life

According to the probability theory, the average of the design service life and the ultimate service life is the average service life of buildings, and the average service life of ordinary buildings is 80 years. Among them, 50% of the existing buildings should have a reasonable service life of more than 80 years; 25% of the existing buildings can achieve 80 years of reasonable service life through maintenance and other measures; 12.5% of the existing buildings can reach 80 years of reasonable service life through overhaul and structural reinforcement; and the service life of remaining 12.5% of buildings should not be extended, and their reasonable service life is 50 years. On a weighted average, the average reasonable service life of ordinary buildings with the same safety guarantee is 70 years.

According to the research data on the safety and durability of building structures [2], for building projects with a design service life of 50 years, the average life should be 88.5 years before the occurrence of impermissible cracking and deformation, and 150 years before ultimate bearing capacity failure due to performance degradation.

It is specified in Article 60 of the Construction Law that “The quality of the ground foundation works and main structure must be ensured for buildings with the reasonable service life”. It can also be understood that the normal service period “with the ensured quality of the ground foundation works and main structure” is the reasonable service life. The design service life is the low limit of reasonable service life. Therefore, it is reliable and reasonable to extend the design service life of buildings to the reasonable service life, and it meets the basic requirements of the Construction Law.

4.3 Value analysis on extension of service life of existing buildings

4.3.1 Value engineering

Value is a measure to assess the degree of benefit of things, and value engineering is also called value analysis. It is an analytical method to realize the necessary functions of a product at the lowest life-cycle cost. Through the functional cost analysis of value engineering, the maximum comprehensive benefit obtainable by the people can be predicted, and the main factors and ways to improve the value can be found out.

The basic calculation formula of value is the ratio of the function the product has to the total cost to obtain the function, that is:

$$V = F/C \tag{1}$$

where: V is value. As long as the value is constantly improved, the society, enterprises and consumers can all get more benefits.

F is the function, being the product and utility provided for the society and enterprises;

C is the cost, being the input made to obtain the function.

4.3.2 Full life cycle value analysis of buildings

The function of buildings is to provide safe, practical and comfortable activity space and environment for people's living and production. The building function is mainly reflected in the length of service life. The cost of buildings includes initial construction cost, operation and maintenance cost and demolition and recovery cost, of which the initial construction cost is the fixed cost that has been invested, the operation and maintenance cost is the dynamic cost varying with the change of use intensity, and the demolition and recovery cost is the predicted fixed cost in the future. To facilitate comparison and calculation, the building function and operation and maintenance costs are normalized according to the annual management needs, and converted into a constant based on the service life, then the calculation Formula (1) of the full life value of the building can be improved to Formula (2):

$$Vn = \frac{N(Fs - Cs)}{Cg} \tag{2}$$

where, Vn is the total value when the service life is N years;

N is the service life;

Fs is the annual amount of function;

Cs is the annual operation and maintenance cost; (Fs-Cs) is the net annual function;

Cg is the total fixed cost, that is, the sum of the initial construction cost and the demolition and recovery cost.

4.3.3 Value increase rate when the building service life is extended

If the basic service life Nj of the building is extended by Nz years, assuming that the annual net function of the extended period is equal to the annual net function of the basic service life, then the increase rate of building value Lv can be calculated with Formula (3):

$$\mathrm{Lv} = \frac{\mathrm{Nz}}{\mathrm{Nj}}\left(1 - \frac{\mathrm{Cz}}{\mathrm{Nz(Fs-Cs)}}\right)100\% \quad (3)$$

where, Cz is the total cost of extending the service life by Z years, including one-time investment expenses such as testing and appraisal fee, maintenance, reinforcement and parts replacement.

It can be seen from Formula (3) that, when the design service life is shortened, that is, Nz < 0, the value increase rate of Lv is negative; when the design service life is extended, i.e. Nz >0, the value increase rate of Lv is positive; when the increased total cost Cz for the extended service life of Nz years is less than the total net function Nz(fs-cs) in the extended service life, the value increment Lv is positive. There is no value in extending the service life if the total increased cost of Cz for the extended service life is greater than the total net function Nz(fs-cs) in the extended service life.

For ordinary buildings, when the basic service life, that is, the designed service life, is 50 years, the average reasonable extended service life is 20 years, and the increase rate of its value is:

$$\mathrm{Lv} = 40\left(1 - \frac{\mathrm{Cz}}{20(\mathrm{Fs-Cs})}\right)\% \quad (4)$$

According to the probability theory, the cost for extending the reasonable service period of 50% buildings by 20 years is “0”, so the increase rate of building value is 40%; the total cost for extending the reasonable service period of 25% buildings by 20 years is 25% of the net function of 20 years, so the increase rate of building value is 30%; the total cost for extending the reasonable service period of 12.5% buildings by 20 years is 50% of the net function of 20 years, so the increase rate of building value is 20%; and the value increase rate of 12.5% buildings is 0; on a weighted average, the average increase in building value over a 20-year service period is 30%. Therefore, it is quite necessary to extend the service life of existing buildings.

4.4 Technical feasibility of extending the service life of existing buildings

4.4.1 Reliability appraisal

Appraising the reliability of buildings is based on probabilistic reliability. Existing buildings differ greatly from one another with many uncertain factors, with different design and construction quality, different maintenance and service environment, and different damage and durability, so it cannot be guaranteed that the reasonable service life of all buildings reaches the design service life even for buildings with the identical design service period. Therefore, it is specified in the Standard for appraisal of reliability of civil buildings that reliability appraisal shall be performed for existing buildings having reached the design service life to be further used [17].

The reliability appraisal of existing buildings mainly includes bearing capacity and durability appraisal of the structure or components. On the basis of full investigation of related design documents and construction acceptance documents, service and maintenance situation, change of application, disasters subjected and the service ambient temperature, humidity, chloride ion concentration, and subsidence, tilting and deformation observation, the extent of corrosion and damage and the aging of the material properties of components important to structure or member connection are tested and measured, when it is necessary to test the bearing capacity and dynamic characteristics of the structures, field test shall be made according to the Technical standard for inspection of building structure, and relevant calculation and analysis will be made according to the investigation and testing results, to make a comprehensive and scientific assessment. Generally, buildings are appraised into the following 4 grades:

Grade A: reliable, no obvious defect or damage, and only normal maintenance is required for the building to enter the target service period;

Grade B, basically reliable, with local surface defect or damage, and normal maintenance and appropriate repair is required for the building to enter the target service period;

Grade C: normal service is already affected, with defect or damage of fairly large scope, and overhaul and local reinforcement is required for the building to enter the target service period;

Grade D: it cannot be used normally further, with obvious defect, damage and deformation, and in the accelerating trend. Measures must be taken, and a decision be made to terminate the service or on the further service period after overhaul and reinforcement.

As limited by the appraisal standard, it is specified in 3.1.5 of the Standard for appraisal of reliability of civil buildings that the appraisal target service period should not exceed 10 years. At present, there are advanced detection instruments such as ultrasound-rebound detection system, reinforced concrete radar detector, reinforced concrete detector, optical microscope and microwave humidity leakage detector. Basically, the testing standard required by the building reliability appraisal standard can be achieved. It is feasible to increase the appraisal target service life by more than 20 years as long as the NDT and the testing level of material aging degree of concealed works such as foundation can be improved.

4.4.2 Maintaining the ultimate bearing capacity of structure or members

For existing buildings to extend the service life, it shall be ensured that the structure or members will not be damaged due to bearing capacity failure in the ultimate service state during the service period. The corrosion, damage, deformation and other diseases that threaten the bearing capacity of structures and members can be solved by means of technical measures such as protection, repair, consolidation and reinforcement. China has developed all kinds of preservatives, protective agent for member protection, all types of binders and cement additives used to repair damage of concrete members, the steel plate pasting technology, steel bar rooting technology, column replacement technology (structure is supported before columns are replaced) for consolidating the concrete structures, the tree root pile and pressure grouting technique for foundation consolidation, and various kinds of building fire protection, waterproof, moisture-proof, thermal insulation and shock absorption, noise reduction technologies, therefore it is feasible to keep the original bearing capacity of existing buildings in the extended service period.

4.4.3 Increasing the durability of structures or members

To ensure the safety and reliability of buildings in the extended service life, the durability of structures or members must be improved. In the service conditions of natural environment, with the elapse of time, the materials of building structure will gradually get aged, with continual degradation of structure performance, which will inevitably lead to injury or even damage, and then affect the service functions and bearing capacity of the structure and the safety of the whole structure [1]. Under normal service conditions, the development of this damage is slow, and it often takes years or even decades. However, in damp and hot, alternating dry and wet environments, cyclic freezing and thawing, the presence of chloride ion and acid, alkali medium and microbial corrosion, wearing, fatigue and other erosion, the damage will accelerate. Therefore, in addition to improving the service environment, it is feasible to meet the durability requirements of buildings in the extended service life by improving the carbonization resistance of concrete, the rust resistance of steel bars and preventing concrete alkali-aggregate reaction damage and other technical approaches, to improve the corrosion resistance and aging resistance of the materials.

1) Improving the carbonization resistance of concrete and the rust resistance of steel bars

Concrete carbonization is a complex multiphase physicochemical process. Concrete is a porous mass, with various capillaries, pores, bubbles and even defects in its interior, media such as CO_2, HCl, H_2SO_4, HNO_2, HF_4, H_2S, P_2O_3, SO_2 and SO_3 in the service environment will constantly enter them, to react chemically with the alkaline hydrates such as Ca(OH)2, $3CaO{\cdot}SiO_2$ and $3CaO{\cdot}SiO_2$ produced in the hydration reaction process of cement, producing $CaCO_3$ and lowering the alkaline of concrete. When this carbonization reaches the surface of the steel bars, and reduces the PH value of the steel bar surface to below 10, it can depassivate the steel bar surface and cause rusting.

Once the steel bar rusts, the bonding force between the steel bar and the concrete decreases, and the expansion of rust makes the concrete protective layer crack and fall off along the bar, accelerating the rusting of steel bars, reducing the steel bar section and lowering the mechanical properties of the members. At the same time, carbonization will increase the concrete shrinkage, cause micro cracks in the concrete, reduce the strength and impermeability of concrete, and rapidly accelerate the rate of concrete carbonization and steel corrosion.

Once carbonization reaches the steel bar surface and after the passivation layer of steel bars is lost, in the presence of both O_2 and H_2O, steel bar electrochemical reaction can occur, so the iron on the bar surface constantly loses electrons and is dissolved in water, the bars are gradually corroded and expand, reducing the strength and elongation, and further leading to crack corrosion, sharply reducing the elastic deformation capacity of steel bars; as a result, they may suddenly break without any sign, posing a great threat to the structural safety.

The actual PH value of concrete can be as high as about 13, when the PH value is over 11.5, it is in the non-carbonized zone, and the steel bars are in the passivated state and will not rust. The PH value of complete carbonized zone is about 7.0, and that between the two zones is the carbonization reflection zone, with the PH value generally limited to 10.5~11.0 as the carbonization depth.

According to the measured carbonization depth, the permissible carbonization time for the continuous service period of concrete can be calculated with Formula (5) [1]:

$$\mathrm{T} = \left(\frac{\mathrm{X}}{\mathrm{Xi}}\right)^2 \mathrm{Ti} \tag{5}$$

Where, T is the permissible carbonization time;

Ti is the service time up to the measured concrete carbonization;

X is the distance from steel bar surface to the carbonization front;

Xi is the measured complete carbonization depth from concrete surface.

When the carbonization time T allowed for the concrete is not enough for the further service period, corresponding measures must be taken for concrete members. China has now developed a variety of concrete surface protective agent and repair agent with organic silane as the main raw material, with super-strong penetration ability, able to block tiny pores and micro cracks on concrete structure surface, prevent erosion of concrete by media such as CO_2 and chloride ion, keep the permeability of concrete, and improve the carbonation resistance of concrete surface layer, therefore it is feasible to maintain the carbonization and rust-corrosion resistance of the structure in the extended service period.

2) Preventing concrete alkali-aggregate reaction damage

In the alkali-aggregate reaction, the high-alkali pore solution formed in the wet environment from various alkali media produced in the hydration process of cement in the concrete pores reacts with the active SiO_2 on the aggregate surface, to produce silicate gel. When the high-alkali solution contains much Na^+ and K^+ but less Ga^{2+}, the resulting silicate gel is more viscous and can absorb large amount of water, causing the concrete to expand and crack. Once the concrete cracks, the water and CO_2 and other media in the air will invade continuously, accelerate the concrete carbonization and steel corrosion, resulting in overall destruction of concrete. It usually takes several years or longer time for concrete affected by alkali-aggregate reaction to crack. Generally, damage of concrete by alkali-aggregate reaction can be prevented by keeping the concrete service environment dry and taking technical measures such as protection against moisture and water.

5. Conclusions and suggestions

According to the full life-cycle cost analysis of buildings, the future cost of operation, maintenance, demolition and recovery will be more than twice the original construction cost. For ordinary high-rise buildings, the full life cycle cost is about 20,000~30,000 yuan; the energy consumption is about 430Kg/m^2; and CO_2 discharge about 950Kg/m^2; all higher than those in developed countries in Europe and America. At present, the initial building energy consumption in China has accounted for 27.5% of the whole society final energy consumption, but the design service life is only 50 years, lower than that in European and American countries, so it is quite necessary to extend the reasonable service life.

According to the interpretation of relevant building codes and technical standards, the ultimate service life is 2.2 times the design service life, the average reasonable service life is 1.4 times the design service life, and the reasonable service life for ordinary buildings is 70 years.

According to the full-life value analysis of buildings, the value of buildings will increase by 30% if the design service life of ordinary buildings is extended from 50 years to the reasonable service life of 70 years.

According to the 2005 Statistical Bulletin of the General Survey of Cities and Towns, by the end of 2005, the building area of urban houses in China’s cities and towns was 16.451 billion m^2, and about 4.676 billion m^2 was built before 1985. In the future, if the service life of existing buildings can be extended for 20 years at 500 million m^2 by annual average, with annual service benefit of 100 yuan/m^2, the annual economic benefit of the whole country will be over 1 trillion yuan.

To extend the design service life of buildings, it is technically feasible to ensure the safety and reliability in the extended service life by means of the reliability appraisal of the structure, maintaining the original bearing capacity of the structure and improving the durability of the structure.

6. Suggestions

(1) Extending the building service life is complex systematic engineering, and will involve the work related to construction laws and regulations, construction management, technical standards, technological innovation, and development of new materials and processes. It is suggested that relevant competent authorities and research institutions include the research on extending the service life of existing buildings in the work agenda, formulate and improve relevant laws and regulations, policies and technical standards, and establish big data library for existing buildings, and make census, statistics, classification and summary for the ownership, applications, construction time, floor area of existing buildings, and their conditions of design, construction, decoration, service, maintenance and the impact by disasters and service environment.

(2) The research on the treatment of demolition building waste should be speeded up, and the difficult problem of insufficient strength stability and durability of recycled concrete aggregate and recycled cement be resolved. It is also suggested that the government level resource tax on the use of natural sand and stone materials, and grant tax reduction and exemption for the use of recycled cement and aggregates as construction wastes, to encourage enterprises to save energy and reduce emission.

(3) Research on the reliability appraisal technology for existing buildings shall be speeded up, and development work be accelerated for new NDT detection and technologies for detecting concealed works such as ground foundations and anti-aging technology for material performance, the testing precision and appraisal level should be continually improved, to not only extend the design service period of ordinary buildings by 20 years, more importantly, the service life of large number of buildings appraised as Grade A and B should be extended for 30 to 50 years, to get more service value of existing buildings.

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