Structural durability and concept system of structural reliability

Yao Jitao, Chen Liuzhuo, Gao Jun, Xin Ren

School of civil engineering, Xi’an University of Architecture and Technology, Xi’an 710055, China

Corresponding author’s e-mail: 15276831997@163.com

Abstract. Research on durability is vital for reliability analysis and control. The main aim is to analyze the deterioration of concrete structures resulting from material degradation. While there is still a large difference in understanding the concept of the structural durability, and a misunderstanding of the relationship among safety, serviceability, and durability, which influence the process of establishing the structural reliability concept system, and the analysis and control of structural durability. Based on former researches and the definition of “condition limit state” in an international standard, the concept of structural durability and the relationship among safety, serviceability, and durability of a structure are elucidated clearly. Furthermore, the basic solution to durability analysis and control is put forward, and the concept system of structural reliability is built. The research will lay the foundation of defining the structural durability uniformly, measuring the structural durability reasonably, and analyzing and controlling structural reliability and structural durability effectively.

1. Introduction

Researches on the durability analysis and control have achieved remarkable achievements, while the definitions of structural durability in different standards can’t reach an agreement until now. Different definitions are listed in Table 1. As shown in table 1, the definitions are varied mainly in service conditions, time domain, and control targets. In terms of service conditions, every standard stipulates the condition for maintenance; every standard other than GB/T 50083-2014 defines external environment or actions; no standard except GB/T 50476-2008 and CCES 01-2004 set a limit to use condition. From the aspect of time domain, some give a specific time limit, e.g. “design working life”; some just give an ambiguous limit, e.g. “a specified period of time”, “a long period of time”, “a predetermined period of time” et al.; some have no time limit. As for control targets, almost all standards, from the view of the damaged structural performance, point that “the deterioration does not impair the performance of the structure below that intended” or “the damaged structures satisfy with the design performance requirements” et al. Among the standards, CCES 01-2004 and GB/T 50476-2008 stress the safety and serviceability particularly. While GB 50153-2008 from the perspective of reliability, points that “the deterioration of material properties does not result in an unacceptable failure probability of the structure”.

Table 1. different definitions of structural durability in different standards

| Standard            | Standard No. | Service Conditions                       | Time Domain           | Control Targets                      |
|---------------------|--------------|------------------------------------------|-----------------------|--------------------------------------|
| Basic of Structure  | EN 1990: 2002| regard to the environment and the anticipated level | design working life | the deterioration does not impair the performance of the structure below that intended |
| Design              | [1]          | of maintenance satisfying with planned   | a specified period of time | the damaged structures satisfy |
Reliability for Structures 2394:2015 [2] maintenance under the influence of the environmental actions a long/period of time with the design performance requirements

Guide to Durability Design and Construction of Reinforced Structure CCES 01-2004 [3] actions that causing deterioration of material properties/ under the intended actions and the anticipated level of maintenance and usage the damaged structures maintain original performance/meet required technical performance (e.g., safety, serviceability et al.)

Unified Standard for Reliability Design of Engineering Structures GB 50153-2008 [4] under a prescribed working environment/under normal maintenance a predetermined period of time/design working life the deterioration of material properties does not result in an unacceptable failure probability of the structure/the damaged structures can be used normally

Code for Durability Design of Concrete Structures GB/T 50476-2008 [5] under the environmental actions, maintenance and usage in design design working life the damaged structures maintain safety and serviceability

Standard for General Terms Used in Design of Engineering Structures GB/T 50083-2014 [6] under normal maintenance - the damaged structures meet predetermined functional requirements

The significant differences on the definitions among different standards make it hard to build a common understanding of structural durability, which affects not only the demarcation, but the measurement, analysis and control of structural durability. Therefore, clarifying the definition of structural durability is a fundamental problem that should be solved first.

Based on previous researches [7, 8] and the condition limit state which was put forward by ISO 2394:2015, the definition of structural durability is elucidated, the relationship among safety, serviceability and durability is clarified. Afterwards, the concept system of structural reliability is built.

2. Structural reliability and structural time-domain reliability

2.1. Structural reliability

In the European standard [1] and the international standard [2], the structural reliability is defined as “ability of a structure or a structural member to fulfill the specified design requirements in the design working life”. While Chinese standards [4, 9, 10] define the structural reliability as “ability of a structure to meet predetermined functional requirements under prescribed time and conditions”. These two definitions seem to be same, but Chinese standards are more inclusive for considering both the structures in design and the existing structures.

According to the above definitions, the concept of structural reliability involves three basic elements: time, condition and function, which are important factors for an accurate understanding of structural reliability and structural durability.

First of all, since the purpose of structural reliability analysis is to predicting the capability of the structure that should meet the predetermined function in a prescribed time, in which the “time” refers to one period in the future. For a structure in design, the “time” means the design working life. For an existing structure, it means the target working life [4].

Secondly, the condition in structural reliability has something to do with scenario, which related to a change in structural conditions or actions [11]. Changes in the usage, environment, actions and some other conditions are possible to make significant alterations in structural states, thus leading to crisis situations. The structural reliability is varied from different setting scenario. For that reason, scenario should be set first during the structural reliability analysis, which is similar to the stipulation “prescribed conditions”. For a structure in design, the prescribed conditions mean normal design, construction, usage and maintenance [4], which are the requirements as well. Under these conditions, all actions and environmental impacts that a structure may withstand throughout their service lives should be taken into account. The environmental impacts mentioned here refer to physical, chemical or biological impacts that may cause deterioration of material properties and further lead to
deterioration of structural serviceability and safety [2]. The mechanical effects that cause the loss of structural materials should also be considered, such as the force of high-speed water scouring, sandstorm encroachment, moving wheels and moving materials’ friction.

Thirdly, the ability of the structure to fulfill its intended function is the core of the structural reliability. For a structure in design, GB 50153-2008 requires structures shall meet the following functional demand throughout the design working life [4]:

- Sustain potential actions that may occur during construction and use;
- Maintain good using performance;
- Maintain sufficient durability;
- Maintain sufficient bearing capacity within the specified time in case of fire;
- Maintain necessary robustness, avoid damage consequences which are not with respect to the cause, and prevent the progressive collapse of the structure in the case of accidental events, such as explosion, collision and human error.

The above-mentioned performances are customarily divided into three aspects, namely safety, serviceability and durability. Specifically, (1), (4), (5) are generally classified as safety, (2) is serviceability and (3) is durability.

Moreover, the performances are also divided into three aspects in international standards even the regulations of structural durability are not listed clearly. ISO 2394:2015 requires structures shall meet the following performance demand with appropriate degree of reliability [2]:

- Withstand serviceability and functionality under all expected actions during their service lives;
- Sustain extreme, frequently repeated, permanent, and environmental actions in construction, anticipated use, as well as decommissioning; providing safety and reliability which inconsistent with damage and failures.
- Maintain sufficient robustness when suffer severe damage or cascading failure by extraordinary and possibly unforeseen events, such as natural hazards, accidents, or human errors.

The structural reliability consists of safety, serviceability and durability according to the ISO 2394:2015 [2]. One thing should be mentioned is that the structural durability requirement is reflected in (1).

2.2. Structural time-domain reliability

Time, condition and function are three basic elements to describe structural reliability which should meet the corresponding requirements, called specific time, prescribed condition, predetermined function respectively. Supposing two of the above elements meet the requirements, estimating whether the third element meets the requirements is a primitive method for reliability assessment.

Generally, the structure is designed to meet the requirements of time and condition, and the structural reliability is finally determined by comparing the actual function and predetermined function. The structural reliability is defined in this way at present. While the definition can also be determined by designing a structure to meet the requirements of both condition and function, and comparing the use time and specified time. The second method has been widely used in the reliability researches of mechanical and electronic products [12-14]. Even from different perspective, the consequences of these two ways are same [7, 8].

Yao et al. [7, 8] defined the second way as structural time-domain reliability, specifically expressed as “ability of a structure or a structural member to fulfil the time requirements under prescribed conditions and predetermined functions”. If the maximum use time of the structure under the predetermined functions is defined as the service life, the structural time-domain reliability can also be simply defined as “ability of a structure or a structural member to fulfil the service life under prescribed conditions and predetermined functions”.

From the above we can see that the structural reliability and the structural time-domain reliability are same, while they are from different perspectives to determine the structural reliability. The former is described from the perspective of function, while the latter from time. If probabilistic measures are
used, structural reliability and structural time-domain reliability should be equal in the same time, condition and function [7, 8, 13].

3. Structural safety and structural serviceability

Structural safety and structural serviceability, referring to the ability of a structure to complete the predetermined function on safety and serviceability respectively, are both belong to structural reliability. In the analysis of structural safety and structural serviceability, the limit states expressing the functional requirements should be the specific criteria to determine whether a structure is safe or serviceable respectively. They should also be the specific criteria to distinguish the safety and serviceability of a structure.

The limit states are divided into three categories: ultimate limit state, serviceability limit state, and condition limit state [2]. Among them, the condition limit state corresponds to the following situations:

- An approximation to the real limit state that is hard to define or calculate.
- Local damage (including cracking) which reduces the structural durability or affects the appearance or performance of a structural or non-structural member.
- Additional limit state thresholds in the case of a continuous deterioration of functions.

Although (1) and (3) have been introduced in ISO 2394:2015, more detailed explanations are given below.

For the first situation, theoretically, the requirements for durability are already covered by the requirements for safety or serviceability in a certain period of time. In other words, the limit state of durability is already reflected by the ultimate limit state or the serviceability limit state. However, in practical project, it might be helpful to set a specific intermediate limit state, typically named “initiation limit state”, which is related to durability such as using depassivation of steels as a limit state, or related to non-critical condition such as using the elastic limit as the ultimate limit state. The initiation limit state does not mean a real limit state, but setting such limit state is conducive to controlling the structural durability, so as to better control the real limit state.

For the second situation, the condition limit state refers to the intermediate limit state related to local damage. e.g. “setting the cracking time as the intermediate limit state to avoid excessive cracks affecting the durability of reinforced concrete members”. The above method can not only better control the structural durability, but ensure the good performance or satisfied appearance of structural and non-structural members.

For the third situation, the real limit state generally refers to sudden damage which caused by a little change of exposure or circumstances. While in some cases, the real limit state is difficult to control the intermediate process when damages gradually formed. A good solution for the problem is to divide the unfavorable state of the structure into several loss levels. Taking seismic analysis for example, firstly, the unfavorable state is divided into initial damage, maintenance, collapse, etc., and then they are controlled step by step as an intermediate limit state.

In conclusion, the condition limit state is mainly proposed from the perspective of control. The purpose is to use an approximate or additional limit state to control the actual limit state. The condition limit state belongs to ultimate limit state or serviceability limit state in essence, rather than the third ultimate state paralleled to them. Therefore, there are only two basic classifications of structural ultimate states at present, which are ultimate limit state and serviceability limit state.

There is also a clear correspondence between limit states and structural functions, which means that a division of the limit state is also a division of the structure function. According to the meanings and specific explanations of ultimate limit state and serviceability limit state, they correspond to safety and serviceability respectively. Correspondingly, structural reliability, describing the structure capability to fulfill predetermined functions, should also be divided into two categories, namely, structural safety and structural serviceability, which are the basic classifications of structural reliability [7, 8].
4. Structural durability

4.1. Concept of structural durability

Generally, damage which affects the structural durability accumulates slowly over time and gradually leads to the deterioration of structural performance. At present, the researches on structural durability are mainly from a time perspective, while this is not a sign of identifying structural durability, because the researches of structural safety and structural serviceability are also considering time sometimes, such as the stiffness of RC member and the crack width changing with time, etc., these are not belong to structural durability.

In order to define the concept of structural durability, the research content and purpose should be comprehensively investigated at first.

The core content of the durability research is damage to structural materials. The performance of a system, from the view of Systems Science, depends on the property, quantity, and relationship of system elements. Analogously, the reasons that cause the deterioration of performance of members can be divided into three parts: deterioration of material performance, loss of materials, damage to the internal structures, which can be collectively referred to as material damage.

Material deterioration mainly refers to the performance degradation which caused by the change of chemical compositions or properties of materials (including the loss of crystal water of cement) under the long-term effects of chemical, physical and other factors, such as the erosion of the external environment, alkali-aggregate reaction inside the concrete, or action of long-term high temperatures. Material deterioration is the core content of the structural durability research, and is even used as a sign to define whether it is a durability problem. However, in terms of materials alone, the deterioration of component performance is not entirely due to the deterioration of mechanical properties of materials. For example, the loss of concrete surface which caused by long-term high-speed water scouring, sandstorm encroachment, moving wheels, moving materials’ friction, and any other mechanical or physical factors, even not changing the chemical composition and properties of the materials, can also causes a decline in the performance of the components, so they are at the core of structural durability studies as well.

The damage to the interior of the members, referring to changes of continuity of material, bond between steel and concrete, friction connection between high strength bolts and steel plates, etc., can also have a direct impact on the performance of members. This kind of damage caused by long-term effects of physical factors (freeze-thaw cycles or physical weathering, etc.), rather than mechanical factor, such as stressed crack (including fatigue crack), rebar slip and high strength bolts slide, are at the heart of structural durability studies.

The main content of the durability research is the effect of material damage on structural performance and states.

In view of whole structure, studying material damage alone is not enough, the adverse effects on structural performance and states should be further investigated, which would be the key point to distinguish the structural durability and material durability. For instance, after analyzing the corrosion of steel bars, it is necessary to further investigate the influence on the bonding performance between steel bars and concrete, the material continuity, the surface, the stiffness and deformation, and even the bearing capacity of components. When conducing further investigations, the structural performance and states can be studied within a set time under the influence of material damage, or the service life of the structure can be obtained under the condition that the structural performance and states are not lower than the expected, in which the influence of material damage on structural performance and states is reflected implicitly.

The purpose of the durability research is to determine whether the ability of the structure meet functional or time requirements.

Determining whether a structure meet the requirements of function or time under the prescribed conditions is the ultimate purpose of structural durability research, because the structural durability is subject to structural reliability. Analyzing service life of the structure is an important part of durability
research. However, present study is not enough in a strict sense, because it’s just an analysis and prediction of the service life, rather than an estimation of the relationship between service life and expected time. Similarly, estimating the relationship between the influence of structural material damage on structural performance and states within a set time and corresponding limit states or corresponding functional requirements is also essential and vital. So it’s not hard to obtain that the purpose of durability research is to determine whether the ability of the structure meet functional or time requirements under the consideration of structural materials damage.

In conclusion, the core content of the structural durability research is material damage, and the main content is its effect on structural performance and states, and the purpose is to determine whether the ability of the structure meet functional or time requirements. The research on structural durability is graphically showed in Figure 1.

As mentioned above, structural durability is a special part of structural reliability. Therefore, according to the concept of structural reliability and structural time-domain reliability, the concept of structural durability can be defined as below. Regardless of which definition is used, the structural durability can be measured by probability.

- Ability of a material to meet its working performance and a structure to meet its predetermined functional requirements under prescribed time and conditions, in which “ability of a material to meet its working performance” means the ability of a material to resist damage;
- Ability of a structure or a structural member to fulfil the time requirements under prescribed conditions, predetermined material working performance and structural functions.
- Ability of a structure or a structural member to fulfil the service life under prescribed conditions.

The “predetermined functions” in above definitions refer to safety and serviceability, corresponding to ultimate limit state and serviceability limit state, respectively. The principle is not to spend too much unexpected funds for maintenance and repair when setting these predetermined functions, or setting the lowest expectation level of structure performance and states. when analyzing and controlling the structural durability, in principle, all actions and environmental effects under the specified conditions should be taken into account. After these, the results of comparing the relationship between service life and required time, or between the actual functions and predetermined functions are completely equivalent.

4.2. The relationship among structural safety, serviceability and durability
The relationship among structural safety, serviceability and durability is considered to be parallel in EN 1990:2002 [1], ISO 2394:2015 [2], and GB 50153-2008 [4], as show in Figure 2. While conceptually, structural durability belongs to structural safety or structural serviceability. The basic classifications of structural reliability are still structural safety and structural serviceability.
Fig. 2 the relationship among structural safety, serviceability and durability in EN 1990:2002, ISO 2394:2015, and GB 50153-2008

As mentioned in 4.1, structural durability which related to material damage is a special part of structural reliability, and therefore a special part of structural safety or structural serviceability. Structural durability is not independent from structural safety and serviceability for a couple of reasons: First of all, the reason why the above standards tend to separate structural durability from structural safety and structural serviceability is that the division principle is the failure mechanism. While actually, the division principle should be the limit states, only involving the structural states. Secondly, in the analysis of structural safety and structural serviceability, structural durability which represents damage of materials cannot be avoided. Otherwise, it is difficult to reflect the actual structural safety and structural serviceability. Thirdly, the durability analysis should not only analyze material damage, but also further investigate the impact on the structure performance and states, and determine whether the structure is safe or serviceable, which is the main purpose of durability analysis. Present reliability research often assume that structural performance does not change with time, and if a degradation does exist, it will be considered as durability research. However, we can not consider the structural durability is completely independent from the structural safety and structural serviceability for durability research is only a workaround of reliability research when considering structural performance degradation. Actually, The structural durability is compatible with the structural safety and structural serviceability, and its attribution depends on the structural state in analysis.

On the whole, the control standards of durability can be divided into two categories: new limit states, such as depassivation of steels etc, and condition limit states (mainly refer to the intermediate limit states). The proposal of these new limit states, such as the amount of chlorion on the surface of steel bar reaches the critical point [16-18], depassivation of steels [19], impending corrosion-induced cracks in concrete cover [20, 21], the width of corrosion-induced crack does not exceed a limited value [22] etc, is to control the influence of material damage on structural functions. These kind of limit states are supplements to serviceability limit state to ensure the structural serviceability. While, some other special standards to control structural states which not equal to actual limit states are proposed. For example, in order to prevent the corrosion of steels, the carbonation depth is limited to a certain value [23, 24], even if the concrete carbonation depth reaches the limit, it generally does not cause cracking of cover concrete and would not reach serviceability limit state. These kind of standards are equal to the condition limit states provided in ISO 2394:2015, whose purpose is to ensure a structure does not exceed the actual limit state, thereby maintain serviceability.

The above two kinds of standards are subordinate to the serviceability limit state, so the corresponding durability should be classified as serviceability. In most cases, durability is attributed to serviceability to avoid serious material damage that affects the use and threatens the safety of the structure. It is similar to the way in ISO 2394:2015. While in some other situations, material damage may directly threaten the structural safety, in which durability should be classified as safety.

For example, the exposure that full of high concentration of corrosive medium and moisture makes it difficult to detect or monitor structural members effectively. It will increase the possibility for lacking of timely detection of serious damage to structural materials. In order to ensure an adequate
bearing capacity, prevention measures should be strengthened, material damage should be fully considered, and standards that control material damage should be more rigid. The above situation related to structural safety directly, and the condition limit state equals to ultimate limit state. For these reasons, durability should be classified as safety.

For another example, an existing structure is continues to be used in harsh environment in a number of years then to be dismantled. In order to determine whether the structure can be used safely before demolition, the impact of material damage on the bearing capacity needs to be considered qualitatively and quantitatively, the requirements of structural safety should depend on the ultimate limit state. In this situation, durability should be classified as safety as well.

In conclusion, structural durability is a special part of structural reliability (including structural safety and structural serviceability). Its attribution depends on the structural state in analysis. If the structural state is ultimate limit state, it belongs to safety; if it is serviceability limit state, it belongs to serviceability. Control standards of durability like new limit states and condition limit states are supplements to serviceability limit states or ultimate limit states. In most cases, durability is attributed serviceability, while in some other situations, durability should be classified as the safety.

5. Concept system of structural reliability

Figure 3 shows the concept system of structural reliability. As seen in Figure 3, structural reliability and structural time-domain reliability are same from different description perspectives: function or time. Both of them can be divided into structural safety and structural serviceability corresponding to ultimate limit state and serviceability limit state respectively. Both of the above limit states cover condition limit state whose purpose is to use an approximate or additional limit state to control the actual limit state. In structural reliability, structural durability is a special part relating to material damage, belonging to structural safety or structural serviceability. Same results will be obtained in the analysis of structural safety, serviceability and durability by the method of structural reliability or structural time-domain reliability.

6. Conclusions

This study has established a concept system of structural reliability based on the new durability concept and the conditional limit state proposed in ISO 2394:2015, which will lay the foundation of defining the structural durability uniformly, measuring the structural durability reasonably, and analyzing and controlling structural reliability and structural durability effectively. The following conclusions can be made:

The concepts of structural reliability and structural time-domain reliability are elucidated. Structural reliability and structural time-domain reliability are completely equivalent, but from different description perspectives: function and time, respectively.
Condition limit state, which proposed in ISO 2394:2015, is an approximate or additional limit state to control the actual limit state. In essence, condition limit state belongs to ultimate limit state or serviceability limit state, rather than a new ultimate state paralleled to them.

The concept of structural durability is elaborated by explaining the core content, main content and purpose of durability research. Knowing that the structural durability which related to material damage is a special part of structural reliability, the concept system of structural reliability is established.

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