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buildings Article Determining Concrete Structure Condition Rating Based on Concrete Compressive Strength Henny Wiyanto 1,*, Chaidir Anwar Makarim 1, Onnyxiforus Gondokusumo 1, Januar Parlaungan Siregar 2 , Agustinus Purna Irawan 3, Tezara Cionita 4 and Najid Najid 1 Citation: Wiyanto, H.; Makarim, C.A.; Gondokusumo, O.; Siregar, J.P.; Irawan, A.P.; Cionita, T.; Najid, N. Determining Concrete Structure Condition Rating Based on Concrete Compressive Strength. Buildings 2022, 12, 776. https://doi.org/10.3390/ buildings12060776 Academic Editor: Francisco López Almansa Received: 2 May 2022 Accepted: 4 June 2022 Published: 6 June 2022 Publisher’s Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affil- iations. Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). 1 Civil Engineering Department, Faculty of Engineering, Universitas Tarumanagara, Jakarta 11440, Indonesia; chaidirm@pps.untar.ac.id (C.A.M.); onnyxiforusg@ft.untar.ac.id (O.G.); najid@ft.untar.ac.id (N.N.) 2 College of Engineering, Universiti Malaysia Pahang, Gambang 26300, Malaysia; januar@ump.edu.my 3 Mechanical Engineering Department, Faculty of Engineering, Universitas Tarumanagara, Jakarta 11440, Indonesia; agustinus@untar.ac.id 4 Department of Mechanical Engineering, Faculty of Engineering and Quantity Surveying, INTI International University, Nilai 71800, Malaysia; tezara.cionita@newinti.edu.my * Correspondence: hennyw@ft.untar.ac.id Abstract: The need for concrete condition assessment for existing buildings increases because of high disaster vulnerability levels, as well as a large number of buildings that have reached their age of use. Currently, there is not any standard reference for assessing concrete condition rating yet, so a concrete condition assessment method that can be measured quantitatively needs to be developed. The developed concrete condition assessment method combines concrete condition assessment based on visual inspection and testing. Assessment measures start with an assessment of visual inspection results, which is continued with concrete compressive strength testing. This article contains a concrete condition assessment based on concrete compressive strength testing. This method determines the concrete condition rating scale using five condition ratings as a reference for building condition assessment. The limit value of each condition rating is taken from concrete compressive strength values that are structurally sufficient, according to the structural concrete requirement code for buildings. Concrete compressive strength values have resulted from non-destructive tests and destructive or loading tests. Building condition rating (BCR) value determination factors in the effect of structure element damage towards building structure and concrete testing result accuracy rating, and also can decrease inaccuracy towards concrete quality condition rating determination on scale limit values, and minimize error risks in determining damage condition rating. The resulting method has the advantage of assessing structure element condition rating and building condition rating (BCR) that can be measured quantitatively, has five assessment scale ratings that can portray building conditions having to be demolished, and calculates structure element critical weight. Keywords: condition rating; building assessment; concrete structure; concrete compressive strength 1. Introduction Concrete quality condition rating determination is a procedure where concrete struc- ture condition is assessed based on the existence of field concrete quality discrepancy to the design concrete quality. The need for building condition assessment is currently rising because of a relative increase in natural disaster risk and the number of buildings that have reached their designed life expectancy. Periodical assessment of a building is conducted to ensure building reliability. Building reliability requirement assessment in- cludes fulfilling building safety, health, comfort, and ease of use requirements. One of the safety requirements includes building structure requirements. To fulfill building safety requirements, existing buildings need to be maintained, repaired, or even demolished if building conditions cannot be maintained [1]. Buildings 2022, 12, 776. https://doi.org/10.3390/buildings12060776 https://www.mdpi.com/journal/buildings Building owners or building management frequently ignore a building's condition as long as it is still operational, and they do not practice proper building assessment due to cost considerations. However, building condition assessment can lower the risk of further building damage. Ignoring it like that can increase the risk of building users' safety and comfort and result in even higher reparation costs than the assessment cost. Assessment is not only conducted on post-disaster buildings or deteriorating buildings but also healthy buildings. Assessment results will describe the building condition and can provide the possible steps needed for buildings in bad conditions [2]. The first step to identifying building structure conditions is conducted by control inspection in the form of visual assessment. The lack of control inspection can speed up the building damage process and will result in damage reparation costs. In addition, control inspection will affect a building's functionality [3]. Visual assessment is the first measure in evaluating a building structure for continuous use or change, analyzing strength or deformation, and determining maintenance and rehabilitation needs [2]. Material condition rating on existing buildings is conducted using the visual assessment method, as well as testing composed of non-destructive and destructive testing from field and laboratory [1]. Building structure condition assessment can be conducted in two ways: early assess- ment and structure detail assessment. In early assessment, technical documentation study and visual assessment are performed. In structure detail assessment, reliability level is determined based on structure evaluation results after identifying existing building mate- rial quality. Existing building material quality is obtained from an arrangement of tests, non-destructive or destructive. In buildings with concrete structures, concrete material quality can be identified from testing results in the form of concrete compressive strength, concrete homogeneity quality, and reinforcing steel quality. Existing reinforced concrete material quality data will be used as input in building structure analysis to identify the existing structural component's ability to carry the design load. This building structure condition assessment is needed to identify existing building condition ratings (BCR). The condition rating is a numerical indicator that functions to give a rating. Assessment is meant to evaluate the real condition of the existing building structure, which shows the existence of a safety factor that is adequate against the load [1]. Concrete quality condition rating that is determined to perform reliability assessment needs to have a reference rating as a condition comparison scale. Therefore, an acceptable value is needed [4]. However, there is a problem, which is the method by which an acceptable structure condition rating is identified. Therefore, the structure reliability level can be determined based on the design target reliability level [5]. Reliability is the ability of a structure or structure element to fulfill the specific requirements in carrying the design loading according to the condition determined within a specific timeframe. A structure has the right reliability level if it fulfills the requirements and reaches a specific target level against the serviceability limit state, ultimate limit state, and structural integrity. Several condition rating assessment scales have been developed worldwide to overcome the qualitative nature of condition rating assessment based on visual assessment. The scale provides a measured condition in terms of damage and the proper reparation steps [6]. Condition rating assessment that is already developed using a concrete condition ratio scale is a concrete condition rating assessment based on visual examination [6–11]. Aside from that, there are also several researchers that have already developed concrete condition rating assessments based on concrete compressive strength testing with the destructive and non-destructive concrete testing types [12–14]. Concrete damage condition rating on existing buildings uses data from visual assessment, hammer test, ultrasonic pulse velocity (USPV) test, half-cell potential HCP test, and carbonation test results. The concrete condition rating scale and reference refer to the British Standards Institution [12]. Risk rating assessment on existing buildings uses data from hammer tests. Scale and reference are determined based on rebound value [13]. Bridge condition rating assessment uses data from the visual assessment, crack factor, and non-destructive testing factor by taking into account the important weight value that is processed with the analytical hierarchy process (AHP) method. Non-destructive tests consist of resistivity meter, ultrasonic pulse velocity (UPV) test, and hammer test [14]. Concrete condition rating assessment is highly needed to portray all building condi- tions that can happen in situ, which is anywhere between the best condition rating and the worst—in which case the building cannot be used anymore. To implement this assessment, a scale and reference that can accommodate all BCR possibilities measured quantitatively for existing buildings need to be developed. This research develops a concrete condition rating assessment method to determine concrete structure condition rating based on in situ concrete compressive strength. The assessment method developed in this research is a method with the following novelty: - Has a condition rating scale that can be used to assess a building up to the worst condition, where a building cannot be maintained anymore and has to be demolished. - - Takes the building structure element's critical weight into account. Minimalizes inaccuracy in condition rating determination from the in situ concrete compressive strength that exists within the limit point. - Determines BCR based on concrete compressive strength with higher reliability to avoid the risk of building failure. The resulted assessment method is used to identify whether the building is in good condition, requires concrete compressive strength testing, requires structure reinforcement or load reduction, or is no longer usable. This assessment method exists on the limit of the building examination measure and is not included in the structure redesign process. This examination measure consists of in situ building damage survey, visually or user testing, and building damage analysis using the resulted assessment method. If assessment results show that the building is in a condition that requires structural reinforcement or load reduction, the following step will be left up to the structure consultant to begin structure reinforcement design. This assessment method is used during the building's routine maintenance periods to provide a feeling of safety and comfort to building users. 2. Materials and Methods The concrete condition rating assessment method is meant to evaluate existing concrete conditions towards building structure safety that is determined based on visual inspection and in situ testing. Based on the terms of SEI/ASCE (2000), assessment begins with a visual inspection, then is followed by in situ testing. Visual inspection assesses physical damage on the concrete surface in the form of cracks, scaling, spalls, and others [15]. Wiyanto et al. (2021) determined twenty types of concrete damage caused by poor implementation that is assessed with a visual inspection. Every damage type has different condition rating values. Concrete damage can happen because of environmental factors, such as chemical factors and disasters. Damage types resulting from those factors have different shapes and condition rating values from damage resulting from poor implementation. Concrete condition rating assessment results with a visual inspection will show whether assessment in the form of testing needs to be implemented on the building. Then, testing is conducted with in situ testing in the form of non-destructive and destructive or loading tests. This assessment result shows whether the building is in good condition and can be used, the structure needs to be strengthened, or weight needs to be reduced. If it needs structure reinforcement or load reduction, then it must be followed with a structured design that considers the compressive strength and flexure strength implemented by the planner consultants. This article is limited to building condition rating (BCR) assessment based on concrete compressive strength testing during the building assessment phase and does not include the structural design phase. The condition rating is determined with the following steps: - Determining condition rating scale that will be the reference in performing exist- ing building concrete structure condition rating based on the concrete compres- sive strength. - Determining structure element condition rating and BCR by referring to the resulting rating scale. 2.1. Condition Rating Scale and Reference Assessment development is conducted by determining a concrete condition rating scale and reference for assessment based on concrete compressive strength testing, which is equal to the assessment based on a visual assessment to be applied in Indonesia. For the sake of comparison, a literature study has been conducted regarding concrete condition rating scale and reference [9,12,16–18]. Currently, there is no basic standard for concrete condition rating assessment based on testing and visual assessment. The existing standard is a standard for concrete compressive strength testing processes. To determine building concrete condition rating, a measuring tool in the form of a condition rating scale and reference is needed. Scale and reference are determined based on concrete damage conditions and concrete compressive strength requirements that are described from very good to very bad conditions. Very good means that the building entirely fulfills the design concrete compressive strength requirements. Very bad means that the building is in such a low concrete quality condition that the building cannot be used anymore or has to be demolished. For a lower concrete compressive strength condition than the design condition, the reduction amount needs to be determined, as well as the steps needed to handle it on each level. The value on each scale limit point is determined based on the concrete compressive strength acceptance value for high-rise building structures according to Indonesian National Standards [19,20]. The acceptance value of each condition rating is determined by the ratio of the in situ concrete compressive strength value to the design concrete compressive strength value. In situ concrete compressive strength is taken from in situ testing results that are implemented with non-destructive or destructive testing. Design concrete compressive strength is taken from structure design according to the building function. This scale can be used as a reference to assess existing buildings in the form of buildings with reinforced concrete structures. The resulted condition rating scale from this research is determined by combining the scale for visual assessment with the scale for concrete compressive strength testing so that it can be used to perform building condition assessment based on destructive and non-destructive testing. 2.2. Condition Rating Determination Concrete testing type identification is grouped based on non-destructive and destruc- tive testing. Concrete testing type identification on buildings refers to standards [1,21]. Debates often happen about concrete compressive strength values that exist near the limit point. To anticipate it, the fuzzy logic method is used to determine condition rating values. The condition rating of each test is determined based on in situ test results referring to the determined condition rating scale and reference. Structure element condition rating is determined for all testing types that are processed with the fuzzy logic method, with the following equation [22,23]: n CRse = i=1 ∑ μf′c,inin n (1) i=1 ∑ μf′c,in where CRse is the structure element condition rating, μf′c,in is the membership function from in situ concrete compressive strength, f′c,in is in situ concrete compressive strength, and in is the condition rating from the reviewed point. The condition rating is determined based on f′c,in which results from each test type, destructive or non-destructive. The concrete compressive strength testing type used in this assessment method is the hammer test or ultrasonic pulse velocity (UPV) test for the non-destructive test and the core drill test or loading test for the destructive test. Condition rating resulting from concrete compressive strength testing is determined based on the membership function from the concrete compressive strength values on each scale. Condition rating from concrete compressive strength value is determined based on the membership function from in situ and laboratory testing results. The membership function is used to map out concrete compressive strength into the membership degrees with a shoulder-shaped curve representation function [22,23]. Condition rating boundary is taken from the determined concrete condition rating scale and reference, which is very good, good, medium, bad, and very bad. The boundary point uses a comparison between in situ and design concrete compressive strength. The shoulder curve portrays the membership function on the concrete compressive strength resulting from this research. Each structure element has a different critical risk according to the function of each element in the building structure. Therefore, this building damage condition rating assess- ment will take the critical weight of each structure element into account. Wiyanto et al. (2020) have determined the critical weight for four structure element types, as shown in Table 1. These critical weight values will be used to determine the BCR. Table 1. Structure element critical weight. Structural Elements Critical Weight (w) Shear wall (sh) 1 Column (c) 1 Beam (b) 0.7 Slab (s) 0.5 BCR assessment as a whole based on concrete compressive strength testing is deter- mined with the weighted average method, which takes structure element critical weight into account. This structure element critical factor value is used to assess high-rise reinforced concrete building structures. The BCR is determined with the following equation [12,23]: BCR = ∑nse∑=sn1e=w1se .CseRse w (2) where BCR is the building condition rating, wse is the structure element critical weight, and CRse is the structure element condition rating. The resulted BCR shows the building damage condition with the criteria and the action needed based on the damage condition. BCR similarity, as a whole, can also be used to determine condition rating per floor or building zone. The results from the assessment method can be used to assess all physical conditions of buildings with reinforced concrete structures, whether the building is healthy or collapsed according to the research goals. There are no limits regarding the number of floors, building function or building life in using this method because all concrete compressive strength values used are in accordance with the in situ and design condition of each assessed building. Validation of the concrete damage condition rating assessment method resulted has already been conducted by applying a visual-based assessment method and testing on eleven existing buildings. This assessment method is applied to existing buildings with reinforced concrete structures that have different types, functions, and building life. These buildings are high-rise buildings with between 3 to 45 floors, between 10 to 58 years of building a life, and function as apartments, malls, offices, parking lots, factories, and hotels. Concrete compressive strength testing is conducted with non-destructive testing in the form of hammer test and UPV test. The building condition rating (BCR) value resulting from this method matches the results from the investigation and assessment conducted by the assessor consultant on the same building. 3. Results and Discussion Concrete structure condition rating determination refers to the condition rating scale. Condition rating scale and reference are determined as a value between visual examination- based assessment and testing. This research determines a condition rating assessment scale with five ratings described as very good, good, medium, bad, and very bad, with damage condition and the appropriate follow-up for each rating, from the lightest, which is no repairs needed, to the heaviest where the building has to be demolished. The lowest condition rating can portray the worst condition of a building. For condition rating assessment based on testing, criteria in the form of limit values on each rating are needed. Criteria are determined using the concrete compressive strength acceptance value of the building structure. The acceptance limit value of each condition rating is determined by the ratio between the in situ and design concrete compressive strength values. In situ concrete compressive strength is obtained from in situ testing results. Testing is conducted from light testing in the form of non-destructive testing to heavy testing in the form of destructive testing. This condition rating scale determination as existing building condition rating (BCR) assessment reference up to the condition where the building has to be demolished is a research novelty that has not been portrayed in previous research [6,10,12–14]. Concrete damage condition rating characteristics for each condition rating can be seen in Table 2. Table 2. Concrete damage condition rating characteristics. Condition Rating Description Criteria Damage Condition and Measure 1 Very Good (VG) 2 Good (G) 3 Medium (M) 4 Bad (B) 5 Very Bad (VB) rf′c ≥ 100% f′c,d No damage. No repairs are needed, but routine maintenance is needed. 85% f′c,d ≤ rf′c< 100% f′c,d Light damage. Repair is needed in routine maintenance. 75% f′c,d ≤ rf′c< 85% f′c,d Medium damage. Further testing is needed as soon as possible. 50% f′c,d ≤ rf′c< 75% f′c,d Structure needs to be strengthened, or load needs to be reduced. Heavy damage. rf′c < 50% f′c,d Very heavy damage or critical damage. Cannot be maintained or demolished. Each condition rating has a value limit that is determined based on the percentage from the concrete compressive strength acceptance values according to Indonesia National Standards [19]. Concrete is considered structurally sufficient if the concrete compressive strength is at least 85% based on core drill testing. If the concrete compressive strength is below 85%, loading testing is implemented. If the concrete compressive strength is below 75%, the building can be maintained by implementing a strengthened building structure or decreasing the building load in its usage. The lowest value limit is determined based on assessment results on the questionnaires. If the concrete compressive strength is below 50%, then structure reinforcement or load decrease in building usage is unreasonable in terms of its costs and its risk to the building users’ safety. rf′c is the percentage of in situ concrete compressive strength value (f′c,in) against the design concrete compressive strength (f′c,d). This resulted condition rating scale will be the reference in the next process, which is concrete condition rating determination for the existing upper building structure. In the assessment process, inaccuracy can happen in determining the condition rating of an in situ concrete compressive strength value that exists within the condition rating limit point area. To accommodate this problem, condition rating determination in this research is developed with the fuzzy logic approach. Structure element condition rating is determined based on membership function from the condition rating of each reviewed point. Structure element condition rating is determined for all concrete compressive strength testing types that are implemented on the assessed building structure element. Membership value is determined using the functional approach that is represented by a shoulder curve [22,23]. The shoulder curve portrays membership function from in situ concrete compressive strength (f′c,in) that is compared to the design concrete compressive strength (f′c,d). The boundary point for each condition rating refers to the description and criteria in Table 2. The relationship between the membership function and the in situ concrete compressive strength in each condition rating is illustrated in Figure 1. Figure 1. Membership function from concrete compressive strength. Based on the illustration depicted in Figure 1 is determined membership function on each concrete condition rating which is described in the following equations: • Very Bad Condition Rating rf′c < 50% f′c,d; therefore μf′c,in = 1 50% f′c,d ≤ rf′c < 62.5% f′c,d; therefore μf′c,in = 5 − 8 rf′c rf′c ≥ 62.5% f′c,d; therefore μf′c,in = 0 • Bad Condition Rating rf′c < 50% f′c,d or rf′c ≥ 80% f′c,d; therefore μf′c,in = 0 50% f′c,d ≤ rf′c < 62.5% f′c,d; therefore μf′c,in = 8 rf′c − 4 62.5% f′c,d ≤ rf′c < 80% f′c,d; therefore μf′c,in = 4.57 − 5.71 rf′c • Medium Condition Rating rf′c < 62.5% f′c,d or rf′c ≥ 92.5% f′c,d; therefore μf′c,in = 0 62.5% f′c,d ≤ rf′c < 80% f′c,d; therefore μf′c,in = 5.71 rf′c − 3.57 80% f′c,d ≤ rf′c < 92.5% f′c,d; therefore μf′c,in = 7.40 − 8 rf′c • Good Condition Rating rf′c < 80% f′c,d or rf′c ≥ 100% f′c,d; therefore μf′c,in = 0 80% f′c,d ≤ rf′c < 92.5% f′c,d; therefore μf′c,in = 8 rf′c − 6.40 92.5% f′c,d ≤ rf′c < 100% f′c,d; therefore μf′c,in = 13.33 − 13.33 rf′c • Very Good Condition Rating rf′c ≥ 100% f′c,d; therefore μf′c,in = 1 92.5% f′c,d ≤ rf′c < 100% f′c,d; therefore μf′c,in = 13.33 rf′c-12.33 rf′c < 92.5% f′c,d; therefore μf′c,in = 0 (3) (4) (5) (6) (7) where f′c,d is the design concrete compressive strength, μf′c,in is the in situ concrete compres- sive strength membership function, and rf′c is the percentage of in situ concrete compressive strength value (f′c,in) against the design concrete compressive strength (f′c,d). Based on this membership function value, a concrete condition rating based on testing can be determined with the CRse equation for each non-destructive and destructive testing type. Based on the μf′c,in value on each condition rating (Equations (3)–(7)), the condition rating value (Table 2), and the structure element condition rating equation (Equation (1)), CRse is there- fore determined for each concrete compressive strength value as shown in Table 3. Table 3. Structure element condition rating. Concrete Compressive Strength Structure Element Condition Rating (CRse) rf′c < 50% f′c,d 50% f′c,d ≤ rf′c < 62.5% f′c,d 62.5% f′c,d ≤ rf′c < 80% f′c,d 80% f′c,d ≤ rf′c < 92.5% f′c,d 92.5% f′c,d ≤ rf′c < 100% f′c,d rf′c ≥ 100% f′c,d 5 9 −8 rf′c 7.57 − 5.71 rf′c 9.4 − 8 rf′c 14.33 − 13.33 rf′c 1 The BCR can be determined directly as a whole or can be determined per building floor or zone with the BCR equation (Equation (2)). BCR determination has to take the condition rating value on each floor or zone into account to avoid the risk of building collapse. BCR value is affected by CRse value. Structure element condition rating value (CRse) is determined based on the concrete condition rating value resulting from in situ concrete compressive strength testing, which is from non-destructive and destructive testing. For building structure elements that are tested with non-destructive and destructive testing, structure element condition rating values are not determined by the average values. However, structure element condition rating assessment is taken from concrete compressive strength values resulting from testing with higher reliability to avoid a higher condition rating than the real condition, which can cause building collapse. Concrete compressive strength testing with destructive testing is more reliable compared to non-destructive testing. Because destructive testing is implemented on the building's core concrete, while non-destructive testing is implemented on the concrete surface [24–26]. If non-destructive and destructive testing results exist in different condition ratings, the more reliable result from destructive testing will be taken. If the average concrete compressive strength value between both testing types is taken, it may result in a condition rating that is higher than the destructive testing results, which portrays a better building condition than reality. This will result in a high risk of building collapse. To prove this issue, a simulation has been conducted to a concrete condition rating determination that is taken from the average values resulting from non-destructive and destructive testing. From simulation results, the probability of condition rating increases on each combination. If condition rating values are taken from the average values resulting from non-destructive and destructive testing results, they can be identified. The probability of an increase in the resulted condition rating can be seen in Table 4. Table 4 shows that there is a 22% to 86% probability that the average condition rating value from both testing types is 1 rating higher than the condition rating based on reliability rating. There is even a 4% chance of an increase by 2 ratings. There is a 70% chance that poses a lot of risk on the assessment result, which is a combination of condition rating 3 on the destructive test and condition rating 2 on the non-destructive test. This condition poses a risk to the building safety, keeping in mind that test results on conditions ratings 2 and 3 are the most common conditions in situ. Therefore, the structure element condition rating value (CRse) from the non-destructive and destructive tests implemented in the same location is determined as such: - If the structure element CRse obtained from the concrete compressive strength value resulting from non-destructive testing is not uniform, it means different condition ratings exist, and therefore destructive testing is needed. - - If CRse,nd is random, then perform destructive testing. If the structure element CRse obtained from non-destructive testing exists within the medium or worse condition rating, then destructive testing is needed. - - If CRse,nd ≤ CRse,md, then perform destructive testing. If the structure element CRse obtained from concrete compressive strength testing value resulting from non-destructive and destructive testing does not exist within the same condition rating, then take the condition rating value resulting from destruc- tive testing. - - If CRse,nd ≠ CRse,d, then take the CRse,d value. A loading test is needed if the structure element CRse obtained from concrete com- pressive strength testing value resulting from destructive testing exists within the bad or worse condition rating. - - If CRse,d ≤ CRse,bd, then perform the loading test. If the structure element CRse obtained from concrete compressive strength testing value resulting from destructive testing and loading test does not exist within the same condition rating, then take the condition rating value resulting from loading test. If CRse,d ≠ CRse,lt, then take the CRse,lt value. The determined structure element CRse is used to determine the building condition rating value as a whole (BCR), as shown in Table 5. Table 4. The increment in the condition rating values resulting from the assessment. Condition Rating Based on Testing Condition Rating Non- Based on Destructive Destructive Average Results Testing Condition Rating Based on Reliability Rating Probability Description 4 5 4 5 3 5 3 5 2 5 2 5 3 4 3 4 2 4 2 4 2 4 2 3 2 3 5 5 4 5 5 5 4 5 5 5 4 5 4 4 3 4 4 4 3 4 2 4 3 3 2 3 74% 26% 39% 61% 14% 86% 78% 22% 28% 68% 4% 30% 70% Appropriate Higher rating Appropriate Higher rating Appropriate Higher rating Appropriate Higher rating Appropriate Higher rating Higher rating Appropriate Higher rating Table 5. Building condition rating determination. Structure Element Condition Rating Building Condition Rating CRse,nd random, or e CRse,nd ≤ CRse,md, or se=1 ∑ wseCRse,d CRse,nd ≠ CRse,d ∑e wse se=1 CRse,d ≤ CRse,bd, or ∑e wseCRse,lt CRse,d ≠ CRse,lt se=1 e ∑ wse se=1 where wse is the structure element type critical weight, CRse,nd is the structure element condition rating from non-destructive testing, CRse,d is the structure element condition rating from destructive testing, CRse,lt is the structure element condition rating from loading testing, CRse,md is the medium structure element condition rating, and CRse,bd is the bad structure element condition rating. Structure element critical weight for shear wall and column = 1, beam = 0.7, and slab = 0.5. Non-destructive concrete compressive strength testing uses a hammer test or ultrasonic pulse velocity (UPV) test, and destructive concrete compressive strength testing uses a core drill test or loading test. To explain the proposed testing-based concrete condition rating assessment method, this method is applied to two buildings. These buildings are annotated as Building A and Building B. These buildings are a 13-year-old 8-storey high-rise mall building and a 20-year-old 3-storey factory building. Building A's design concrete compressive strength is 41.5 MPa, and Building B's is 33.2 MPa. Testing is conducted with non-destructive testing in the form of a hammer test. Based on the structure element concrete compressive strength data resulting from in situ testing, a concrete condition rating assessment is implemented on Building A and Building B, the results of which are shown in Tables 6 and 7. Table 6. Building A condition rating assessment. Test Results Element in μf'c,in Number f'c,in rf'c Upper Lower Upper Lower CRse w se BCR (MPa) Bound Bound Bound Bound 1 32.79 2 34.28 3 46.90 4 45.32 5 43.66 6 40.50 7 43.66 8 42.08 9 42.08 10 43.66 11 48.47 12 43.66 13 37.35 14 46.90 15 48.47 0.79 3 0.83 2 1.13 - 1.09 - 1.05 - 0.98 1 1.05 - 1.01 - 1.01 - 1.05 - 1.17 - 1.05 - 0.90 2 1.13 - 1.17 - 4 0.94 3 0.24 1 - 1 - 1 - 2 0.73 1 - 1 - 1 - 1 - 1 - 1 - 3 0.80 1 - 1 - 0.06 3.06 0.76 2.76 1 1 1 1 1 1 0.27 1.27 1 1 1 1 1 1 1 1 1 1 1 1 0.20 2.20 1 1 1 1 0.7 0.7 0.7 0.7 0.7 0.7 0.7 0.7 1.38 0.5 0.5 0.5 0.5 0.5 0.5 0.5 Building A condition rating assessment results show a condition rating of 1.38. Refer- ring to Table 2, Building A can be included in the 'good' condition rating, with follow-up in the form of reparation within the building's routine maintenance scope. However, there are parts of the structural element that exist between the 'good' and 'medium' condition ratings. Therefore, further testing in the form of destructive testing with a core drill test needs to be implemented on that element of Building A. The Building B condition rating test results show a condition rating of 1.96. Therefore, referring to Table 2, it is determined that Building B can be included in the 'good' condition rating, with follow-up in the form of reparation within the building's routine maintenance scope. However, considering the condition rating value of 2.30 in zone 1, it means that zone 1 is within the 'medium' condition. Therefore, further testing in the form of destructive testing with a core drill test needs to be implemented in zone 1 of Building B. Based on this explanation, it can be seen that this assessment method results in a value that can be measured quantitatively to portray a building's condition rating, with follow-up appropriate to the condition of each assessed building. Mapping concrete compressive strength value into the membership function can remove inaccuracy in determining condi- tion rating from each concrete compressive strength value resulting from in situ testing, especially for concrete compressive strength values near the condition rating boundary points [22,23]. Condition rating value can portray a building's performance. Condition rating values are not directly proportional to a building's age. A building that is designed and implemented according to the existing rules is used according to its intended function. It is also regularly maintained along with its usage, which yields a higher condition rating. Table 7. Building B condition rating assessment. Number f'c,in (MPa) rf'c Upper Bound Lower Bound Upper Bound Lower Bound CRse w se BCR Element Test Results in μf'c,in Zone 1 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 33.17 1.00 28.39 0.86 31.27 0.94 29.88 0.90 29.88 0.90 29.88 0.90 28.56 0.86 28.43 0.86 30.38 0.91 26.89 0.81 26.89 0.81 28.39 0.86 28.39 0.86 29.64 0.89 29.88 0.90 29.88 0.90 30.17 0.91 28.05 0.84 - 1 2 3 1 2 2 3 2 3 2 3 2 3 2 3 2 3 2 3 2 3 2 3 2 3 2 3 2 3 2 3 2 3 2 3 - 1 0.48 0.52 0.20 0.80 0.80 0.20 0.80 0.20 0.80 0.20 0.48 0.52 0.48 0.52 0.88 0.12 0.08 0.92 0.08 0.92 0.48 0.52 0.48 0.52 0.72 0.28 0.80 0.20 0.80 0.20 0.88 0.12 0.32 0.68 1 1 2.52 1 1.80 1 2.20 1 2.20 1 2.20 1 2.52 1 2.52 1 2.12 1 2.92 1 2.92 1 2.52 1 2.52 1 2.28 1 2.20 1 2.20 1 2.12 1 2.68 1 2.30 Zone 2 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 35.86 34.28 37.35 35.86 35.86 28.30 31.29 29.88 28.61 34.28 31.29 28.39 35.86 35.86 29.14 35.86 31.29 31.29 26.89 1.08 1.03 1.13 1.08 1.08 0.85 0.94 0.90 0.86 1.03 0.94 0.86 1.08 1.08 0.88 1.08 0.94 0.94 0.81 - - - - - 2 1 2 2 - 1 2 - - 2 - 1 1 2 1 - 1 - 1 - 1 - 1 - 3 0.40 2 0.20 3 0.80 3 0.48 1 - 2 0.20 3 0.48 1 - 1 - 3 0.64 1 - 2 0.20 2 0.20 3 0.08 1 1 1 1 1 1 1 1 1 1 0.60 2.60 0.80 1.80 0.20 2.20 0.52 2.52 1 1 0.80 1.80 0.52 2.52 1 1 1 1 0.36 2.36 1 1 0.80 1.80 0.80 1.80 0.92 2.92 1 1 1 1 1 1 1 1 1 1 1 1.65 1 1 1 1 1 1 1 1 1 Zone 3 1 2 3 4 5 6 7 8 9 10 34.28 34.28 34.28 28.39 32.79 34.28 28.39 26.27 26.05 31.29 1.03 1.03 1.03 0.86 0.99 1.03 0.86 0.79 0.78 0.94 - 1 - 1 - 1 2 3 1 2 - 1 2 3 3 4 3 4 1 2 - 1 - 1 - 1 0.48 0.52 0.87 0.13 - 1 0.48 0.52 0.94 0.06 0.88 0.12 0.20 0.80 1 0.5 1 0.5 1 0.5 2.52 0.5 1.13 0.5 1 0.5 2.52 0.7 3.06 0.7 3.12 0.7 1.80 0.7 1.93 Whole BCR 1.96 4. Conclusions This research proposes an assessment method with a condition rating scale and reference that can be measured quantitatively, and can be applied to perform concrete damage condition rating assessment based on testing on the existing upper building structure. Condition rating scale consists of five ratings that can portray building condition, from best, to worst–in which case the building cannot be used anymore. Each rating is the boundary by a ratio value between the in situ concrete compressive strength value and the design concrete compressive strength value. The determination of condition rating on each testing point on the structure element is processed using the fuzzy logic approach, where condition rating is determined based on membership function. This method can decrease inaccuracy in determining concrete condition rating on the condition rating boundary value. The condition rating is also determined based on concrete testing results with a higher reliability rating so that the resulted method can minimalize the risk of determining a higher condition rating than appropriate to avoid building collapse. The building condition rating (BCR) is determined by considering the critical weight of each structure element against the building structure as a whole. The assessment method can be used to determine BCR in a detailed manner for condition rating per testing point, condition rating per structure element, condition rating per floor, condition rating per zone, and condition rating of the building as a whole. This can also anticipate building collapse caused by the poor condition of part of the building structure. Author Contributions: Writing—original draft preparation, data curation, methodology, H.W.; con- ceptualization, supervision, C.A.M.; validation, formal analysis, O.G.; review and editing, J.P.S.; project administration, supervision, A.P.I.; writing—review and editing, T.C.; resource and visualiza- tion, N.N. All authors have read and agreed to the published version of the manuscript. Funding: This research received no external funding. Data Availability Statement: Data are contained within the article. Acknowledgments: The authors would like to thank Universitas Tarumanagara for providing equip- ment for the research collection data. Conflicts of Interest: The authors declare no conflict of interest. References 1. American Society of Civil Engineers. Guideline for Structural Condition Assessment of Existing Buildings; American Society of Civil Engineering: Reston, VA, USA, 2000; pp. 1–8, 93–104. 2. ACI Committee 201. 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