Chapter 5
The Modified Post-earthquake Damage Assessment Methodology for TCIP (TCIP-DAM-2020)

A. Ilki, O. F. Halici, M. Comert, and C. Demir

Abstract Post-Earthquake damage assessment has always been one of the major challenges that both engineers and authorities face after disastrous earthquakes all around the world. Considering the number of buildings in need of inspection and the insufficient number of qualified inspectors, the availability of a thorough, quantitative and rapidly applicable damage assessment methodology is vitally important after such events. At the beginning of the new millennia, an assessment system satisfying these needs was developed for the Turkish Catastrophe Insurance Pool (TCIP, known as DASK in Turkey) to evaluate the damages in reinforced concrete (RC) and masonry structures. Since its enforcement, this assessment method has been successfully used after several earthquakes that took place in Turkey, such as 2011 Van Earthquake, 2011 Kutahya Earthquake, 2019 Istanbul Earthquake and 2020 Elazig Earthquake to decide the future of damaged structures to be either 'repaired' or 'demolished'. Throughout the years, the number of research activities focusing on the reparability of earthquake-damaged structures has increased, which is a purposeful parameter in the determination of buildings' future after earthquakes. Accordingly, TCIP initiated a research project with a sole aim to regulate and reevaluate the damage assessment algorithm based on the results of state-of-the-art scientific research. This chapter presents the new version of the damage assessment methodology for reinforced concrete structures which was developed for TCIP (TCIP-DAM-2020). In addition, an application of the developed damage assessment algorithm on an earthquake-damaged reinforced concrete building which was struck by Kocaeli (1999) earthquake is presented.

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5.1 Introduction

Since the second quarter of the twentieth century, a number of destructive earthquakes that took place all around the world caused total or partial collapse of structures and resulted in a great number of casualties and negative economic impacts (i.e. 1940 El Centro, 1967 Mudurnu, 1985 Mexico City, 1995 Kobe, 1999 Kocaeli, 2009 L'Aquila, 2011 Christchurch, 2011 Tohoku and 2017 Puebla earthquakes). Post-earthquake site investigations after damaging seismic events revealed that the number of structures demanding a damage inspection could be extraordinary (AIJ/JSCE/JGS 2001; Alberto et al. 2018; Alexander 2010; Erdik 2000; Kazama and Noda 2012; Marquis et al. 2017) and the insufficient number of qualified inspectors makes the execution of damage assessment a great challenge to accomplish on the way of returning back to everyday life. After disastrous earthquakes, a consistent damage assessment methodology is needed for re-establishing the evacuated structures for the accommodation of the locals and prohibiting the residents to enter the critically damaged structures that might collapse during probable aftershocks. Implementing a reliable methodology is vital for avoiding the unnecessary demolition of damaged structures which creates additional burdens to individuals and national economies. Furthermore, considering the large number of buildings in need of inspection after damaging earthquakes, the assessment methodology needs to be rapidly applicable and straight forward. Past damage assessment experiences gained after a number of earthquakes that took place in Turkey (i.e. 1995 Dinar Earthquake, 1998 Adana Earthquake, 1999 Kocaeli Earthquake and 1999 Duzce Earthquake) also indicated that since the assessors on-site have different backgrounds and experience levels, an objective damage assessment and decision-making is not possible without a quantitative and systematic damage assessment algorithm.

In the year 1999, after the earthquakes that struck the north-western part of Turkey (AIJ/JSCE/JGS 2001; Aydan et al. 2000), the Turkish government implemented a change on the state aid policy to the earthquake victims whose houses are collapsed or damaged during seismic events. The new regulation stated compulsory seismic insurance of structures. Consequently, Turkish Catastrophe Insurance Pool (TCIP) was established in 2000 to execute the compulsory earthquake insurance. In 2002, TCIP appointed researchers to develop a consistent, rapid and easy-to-apply damage assessment method to be benefitted after earthquakes. Accordingly, a methodology satisfying the fundamental characteristics expected from a reliable damage assessment algorithm mentioned above was developed for TCIP (TCIP-DAM-2002) for the two most common structural systems used in Turkey; Reinforced Concrete (RC) and masonry structures, respectively (Boduroglu et al. 2013; Ilki et al. 2013). During its development, the methodologies used in widely accepted guidelines that assert the recommended practices for the post-earthquake damage assessment have been benefitted (Anagnostopoulos et al. 2004; Baggio et al. 2007; Grünthal 1998; FEMA 306 1998; New Zealand Society for Earthquake Engineering (NZSEE) 2009; Japan and building disaster prevention association (JBDPA) 2015). The developed damage assessment algorithm, similar to the methodology used in Japan (Japan and building disaster prevention association (JBDPA) 2015), determines the building safety based on the residual energy dissipation capacity of structural members that degrades due to seismic actions. Since its development, a number of adjustments and improvements have been implemented to make the method easier to apply. For instance, in 2015, a quick inspection algorithm was implemented for those structures having a plan area less than 400 m^2, and whose number of stories above the ground level or rigid basement is less than eight. The main motivation for quick assessment methodology was to complete the damage assessment more rapidly for regular structures built in Turkey. The developed damage assessment system, which includes both detailed and quick inspection algorithms, has been presented in a number of education seminars carried out around Turkey (e.g., Istanbul, Ankara, Izmir, Canakkale, Kocaeli, Elazig, Manisa, etc.) that were organized by different institutions (i.e., Ministry of Environment and Urban Planning, TCIP and Turkish Chamber of Civil Engineers). This method has been successfully used by TCIP in the decision-making processes of earthquake-damaged structures after a number of earthquakes that took place in Turkey, including Van (2011), Kutahya (2011), Istanbul (2019), Elazig (2020) earthquakes. The experience and site observations gained through the application of the TCIP-DAM-2002 revealed that, there is a need for an even quicker methodology.

In recent years, TCIP has established a new action to advance the damage assessment algorithm. One incentive for this action was to make the damage assessment framework, if possible, even quicker and easier to apply without any compromise in reliability and objectivity. Another encouragement was to consider the state-of-the-art scientific research executed in the last two decades which can be benefitted in the further development of the damage assessment system either by modifying or further validating the theory behind the methodology. Also, in the last two decades, the number of code-complying structures, which are designed and detailed in accordance with the capacity design principle, is considerably increased. In addition to the damages in vertical members, these structures are expected to exhibit damages in horizontal members. Hence, a need has arisen for a damage assessment method that takes into account the damages formed on the beams as well. Apart from that, instead of an assessment algorithm that mechanically determines the limits to repair or demolish the earthquake-damaged buildings, a novel approach that estimates and considers the economic feasibility of the repair applications in post-earthquake decision-makings would be more beneficial (Ludovico et al. 2017a, b; Martino et al. 2017). By doing so, the algorithm should also consider the cost of nonstructural members' repair because of the fact that a great portion of the budget reserved for the repair applications of earthquake-damaged structures is spent on the non-structural members (Cardone and Perrone 2017; Taghavi and Miranda 2003; Vecchio et al. 2018, 2020).

A novel damage assessment methodology in accordance with the needs stated above has been developed. More than 100 experimental test results obtained from literature were benefitted in the determination of member damage limits and damage modification factors used in the methodology. Also, more than 200 structural performance analyses and 80,000 cost analyses with different damage scenarios have been carried out for the determination of the limits for building damage categories. In this manuscript, although the method is applicable to both masonry and RC structures, due to page limitations, only the damage assessment algorithm developed for RC structures is presented.

5.2 The Revised Version of TCIP Damage Assessment System

5.2.1 Building Damage Categories

After earthquakes, structures in seismic zones suffer different levels of damage as a result of a process in which various parameters play a role, including structural system characteristics, design and construction errors, ground motion characteristics and soil conditions, etc. During post-earthquake damage inspections, the structural damages caused by the earthquake effects shall be observed in the form of cracking, crushing or spalling of concrete, rupture or buckling of reinforcements, sagging in the horizontal structural members, residual drifts, uniform or differential settlements and tilting of the building, etc. The revised version of the damage assessment system uses site observations and simple measurements as input. However, in the background, the building damage categorization is determined by the evaluation of mechanical and financial feasibility criteria based on the input data. The revised system defines six building damage categories as follow.

5.2.1.1 Undamaged Building

This damage category corresponds to a condition where there is no earthquake damage in vertical (i.e. columns and shear walls) or horizontal (i.e. beams) load-bearing structural members. However, it needs to be emphasized that, the structure might contain some damages formed before the earthquake action typically due to time and environmental effects (e.g. corrosion, shrinkage, freeze–thaw cracks) or other mechanical effects except earthquake (e.g. excessive vertical load, soil settlement). The building maintains its pre-earthquake performance and capacity.

5.2.1.2 Slightly Damaged Building

In the case of slightly damaged building, the vertical and horizontal members that form the structural system of the building suffered limited damages in such a way that the damaged members either do not entail any repair or require relatively simple repair applications. Nonstructural elements such as infill walls might experience some damages, but, in general, they are easily repairable. The building predominantly preserves its pre-earthquake performance and capacity.

5.2.1.3 Moderately Damaged Building

Due to the damages in the vertical and horizontal structural members, the performance and capacity of the structure can be decreased to a certain degree in comparison to that of pre-earthquake condition. In addition to the damages in the structural elements, extensive damages in nonstructural elements can be observed. Still, with further investigations and comprehensive engineering evaluations, it is technically and economically possible to repair and strengthen the building.

5.2.1.4 Heavily Damaged Building

In heavily damaged buildings, the damages in the structural members can reach to severe levels. In addition, many of the nonstructural members of the building are substantially damaged. The building may have lost a significant amount of its pre-earthquake performance and capacity. Due to the necessity of wide-scale and comprehensive structural interventions, the repair and strengthening applications for the structure may be far from being economically feasible. Therefore, demolition-and-reconstruction is generally a more convenient option for these buildings.

5.2.1.5 Building to be Urgently Demolished

The buildings where a partial collapse has occurred in at least one story, or the buildings exhibiting easily observable residual displacements are classified in this category. The existing condition of these buildings poses danger to the safety of life and property. Hence, the demolition of these buildings should be prioritized.

5.2.1.6 Collapsed Building

The structural system lost its integrity and the building is collapsed partially or completely. The vertical and horizontal load carrying capacity of the building is entirely eliminated.

5.2.2 Damage Categories for RC Members

The damage categorizations of vertical and horizontal RC structural members are made in accordance with the rules and limits defined in this section and the observed damages. There are five member damage categories defined to be used in the damage assessment algorithm. Details of the damage categories, whose limits are presented in Table 5.1, are given in Sect. 5.2.2.1–5.2.2.5.

5.2.2.1 Type O Damage Category

Regardless of the damages caused by environmental and time-dependent effects (e.g. corrosion, creep, shrinkage and non-seismic ground settlements), vertical and horizontal structural members which do not contain any damage caused by earthquake effects are assigned to Type O damage category.

5.2.2.2 Type A Damage Category

Vertical and horizontal RC structural members which contain at least one crack with a maximum residual width of 0.5 mm that was formed due to earthquake actions are defined as Type A damaged element. The categorization is carried out regardless of whether the cracks are formed due to bending or shear effects. Typical examples of Type A damages are presented in Fig. 5.1 for bending and shear cracks.

5.2.2.3 Type B Damage Category

Those vertical and horizontal RC structural members that contain at least one crack between 0.5 and 3 mm in width or exhibit slight concrete crushing limited to cover are categorized as Type B damaged structural elements. Figure 5.2 shows typical bending and shear damages that are considered to be Type B damage.

5.2.2.4 Type C Damage Category

Vertical and horizontal structural members containing at least one earthquake-induced crack whose width is more than 3 mm or exhibit concrete cover spalling are categorized as Type C damaged structural members. The structural elements

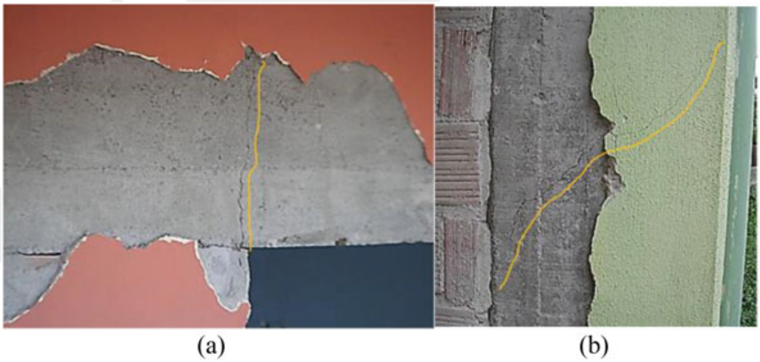

(a) (b)

Fig. 5.1 Examples of Type A Damage Category; **a** flexural damage; **b** shear damage

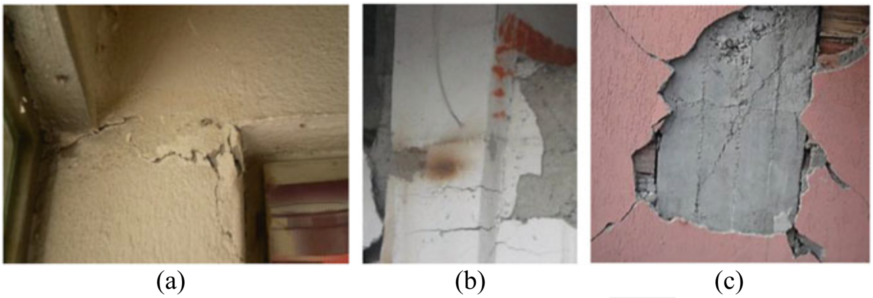


Fig. 5.2 Examples of Type B Damage Category; **a** concrete crushing; **b** flexural crack; **c** shear damage

showing negligible buckling of reinforcement that do not significantly deviate from its alignment are also considered in this damage category. In the previous version of the damage assessment methodology, the members with buckled reinforcement were assigned to Type D damage category. However, as will be discussed in Sect. 5.2.3.2, the structures with Type D vertical elements will be directly assigned to Heavily Damaged building category. Hence, in order not to categorize a whole structure as Heavily Damaged because of a single vertical member with an indistinct reinforcement buckling, this damage level is included in Type C damage category. Figure 5.3 presents representative structural members that are deemed to be categorized as Type C damage.

5.2.2.5 Type D Damage Category

Vertical and horizontal structural members exhibiting core concrete crushing, reinforcement buckling, stirrup rupture or distinctive residual deformations that are formed due to earthquake actions are categorized as Type D damaged elements. Descriptive structural elements having Type D damage are presented in Fig. 5.4.

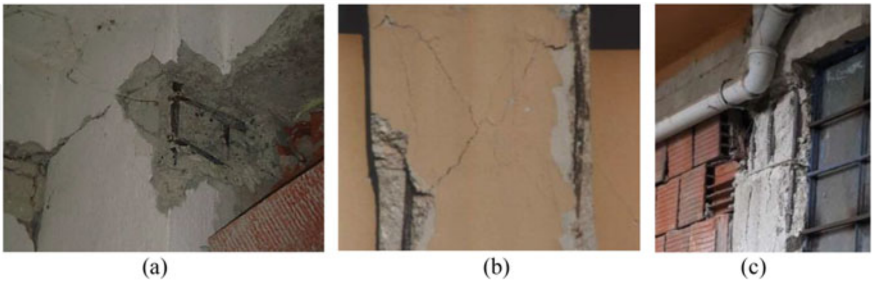


Fig. 5.3 Examples of Type C Damage Category; **a** flexural damage; **b** shear damage; **c** slight buckling of reinforcement

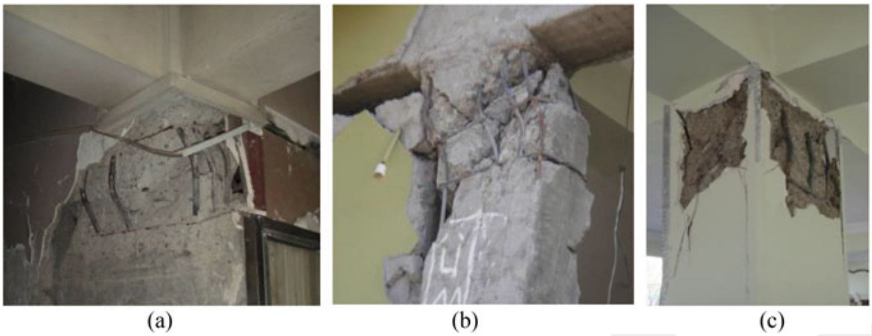


Fig. 5.4 Examples of Type D Damage Category; **a** flexural damage; **b** shear damage; **c** buckling of reinforcement and core crushing

5.2.3 Damage Assessment Algorithm

The damage assessment algorithm consists of a two-stage procedure; (i) exterior assessment and (ii) interior assessment. The evaluation begins with the exterior assessment. Depending on the damage condition of the building, the inspectors proceed to the interior assessment stage with one of the methods defined in Sect. 5.2.3.2.

5.2.3.1 Exterior Assessment

In this stage, visual inspections and measurements will be carried out in regard to the general condition of the subject structure. The exterior assessment will be completed with respect to the following inspection processes.

- If the building is entirely collapsed, the damage categorization of the building is determined as Collapsed Building. If a partial collapse is observed (Fig. 5.5a), the damage assessment is concluded by classifying the structure as Building to be Urgently Demolished.
- If the permanent horizontal residual displacement measured at any story in the building is greater than 1% of the corresponding story height, the building is categorized as Heavily Damaged Building and the assessment is finished. If the horizontal residual displacement at any story is greater than 3% of the corresponding story height, the building is classified as Building to be Urgently Demolished. Figure 5.5b shows a building that suffered from excessive residual displacements that occurred due to seismic actions. The story height (h) and the horizontal residual displacement (d) are schematically illustrated in Fig. 5.6b.
- If the structure exhibits a rigid rotation greater than 2° due to different settlements caused by earthquake effects, the damage category of the building is defined as Heavily Damaged Building and the assessment is terminated. If the rigid rotation

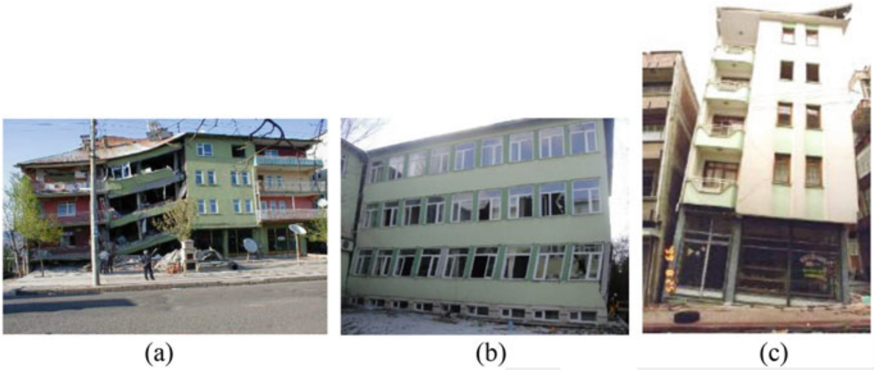
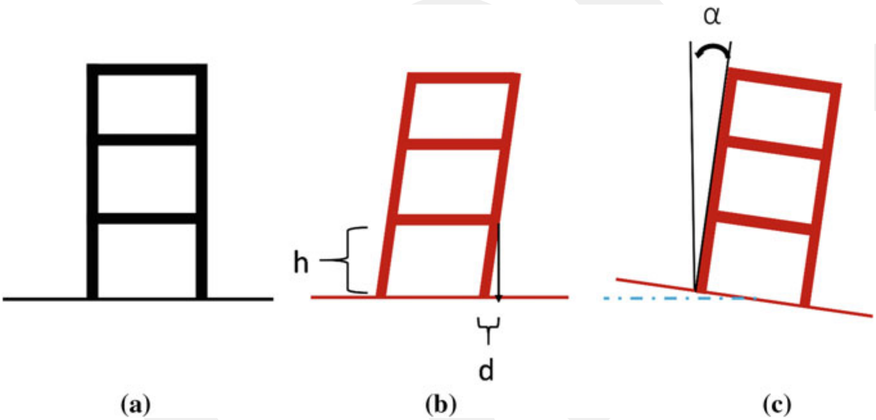

(a) (b) (c)

Fig. 5.5 Damaged structures; partial collapse; **b** excessive residual drift; **c** tilting



(a) (b) (c)

Fig. 5.6 **a** undamaged building; **b** building with residual drift; **c** tilted building

is greater than 4°, the damage assessment is concluded by categorizing the structure as Building to be Urgently Demolished. Figure 5.5c shows a structure that significantly tilted due to rigid rotation at the base. A schematic illustration of the tilting angle is presented in Fig. 5.6c.

If none of the damage conditions stated above exist in the subject structure and there are no obvious structural and nonstructural damages making the entry of the building dangerous, the inspectors proceed to interior assessment stage. Before entering the building, the inspector crew should bear in mind the possibility of aftershock occurrence and need to follow the safety measures.

Table 5.1 Damage limits for RC members

Damage category	Residual crack width	Compression damage
Type O	–	–
Type A	≤ 0.5 mm	–
Type B	$0.5 \text{ mm} < w \le 3 \text{ mm}$	Cover crushing
Type C	>3 mm	Cover spalling
Type D	–	Buckling of reinforcement, core crushing and residual displacement

5.2.3.2 Interior Assessment

In the interior assessment stage, the building damage category is determined based on the damage categories of the vertical and horizontal structural members of the structure that are categorized according to Table 5.1. During the inspection, if the subject structure contains at least one vertical structural member that is categorized as Type D, the building is categorized as Heavily Damaged. In addition, based on the damage conditions given in rapid and detailed inspection procedure, the structures can be classified as Building to be Urgently Demolished. On the other hand, if all the structural members are undamaged, the building is categorized as Undamaged. If there is no vertical structural element categorized as Type D and not all of the structural members are undamaged in the inspected building, the building damage category is determined by applying one of the interior assessment procedures (i.e. rapid inspection procedure and detailed inspection procedure) at the most severely earthquake-damaged story of the structure. It needs to be emphasized that, the rapid inspection procedure is developed and designed to be suitable for the majority of building type RC structures. On site, the inspectors are mostly expected to use the rapid inspection procedure. For the exceptional cases where the building is not in the application limits of the rapid inspection procedure, the inspectors will apply the detailed procedure. In interior assessment procedures, the limit for earthquake-damaged structures to be categorized as Slightly Damaged is determined based on the loss in the structural performance that is caused by earthquake damages. For this, more than 200 seismic performance analyses have been executed considering different damage case scenarios. On the other hand, the limit for Heavily Damaged structures is determined from the repair cost of structural and nonstructural members. The repair costs of structural members exhibiting earthquake damages given in Table 5.1 are obtained from market investigations. In accordance with the findings obtained in the existing researches (Cardone and Perrone 2017; Taghavi and Miranda 2003; Vecchio et al. 2018, 2020) the repair and the cosmetic cost of nonstructural members (i.e., infill walls, floor finishes, ceiling floors, etc.) is approximately assumed to be twice of the structural members' repair cost. In the cost analyses, by relating the structural damages with the structural and nonstructural repair costs, the damage level where the cost of repair becomes financially infeasible is defined to be the limit for the structures to be categorized as Heavily Damaged. This limit is obtained from the results of more than 80,000 cost analyses representing different damage case scenarios.

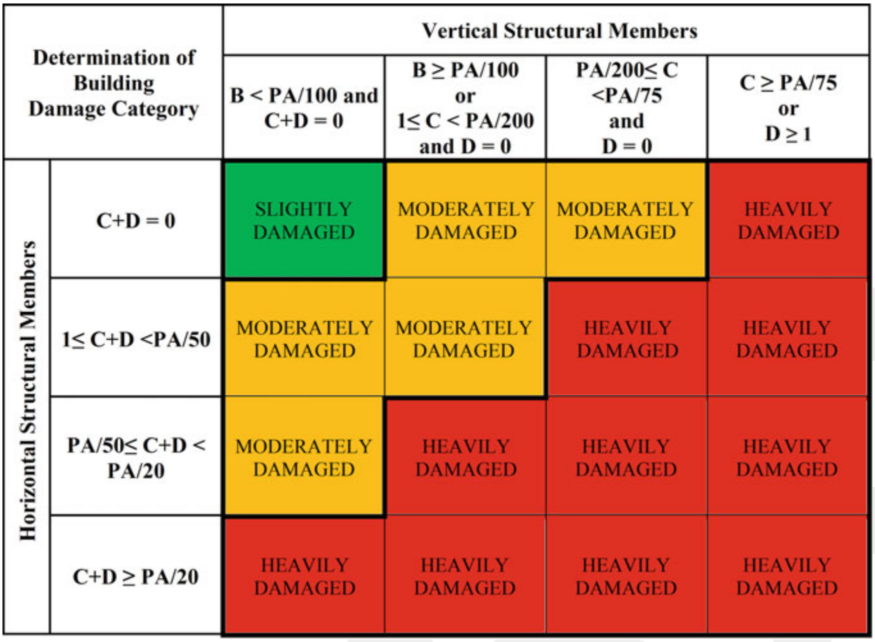
Rapid Inspection Procedure

Rapid inspection method can be employed for the damage assessment of structures whose Plan Area (PA) is less than 600 m^2 and the number of stories above the ground level or rigid basement is less than or equal to 10. In this procedure, the building damage category is obtained based on the number of damaged structural members which are categorized according to the member damage categories defined in Sect. 5.2.2. The number limits for vertical and horizontal structural elements with certain damage categories are generated based on the PA of the inspected structure. Building damage category of inspected structure is determined by considering the following damage limits.

- Damage limits for vertical structural members:
  - The case where the number of vertical members categorized as Type B is less than PA/100 and there is no vertical member classified as Type C and Type D
  - The case where the number of vertical members categorized as Type B is greater than or equal to PA/100 or the number of vertical members categorized as Type C is at least one but smaller than PA/200 and no vertical member is classified as Type D
  - The case where the number of vertical members categorized as Type C is greater than or equal to PA/200 but smaller than PA/75 and no vertical member is classified as Type D
  - The case where the number of vertical members categorized as Type C is greater than or equal to PA/75 or there is at least 1 vertical member classified as Type D.
- Damage limits for horizontal structural members:
  - The case where no horizontal members are categorized as either Type C or Type D
  - The case where the number of horizontal structural members categorized as Type C and Type D is at least one but less than PA/50
  - The case where the number of horizontal members categorized as Type C and Type D is greater than or equal to PA/50 but less than PA/20
  - The case where the number of horizontal members categorized as Type C and Type D is greater than or equal to PA/20.

The damage assessment is concluded through the determination of relevant damage ranges outlined in Table 5.2 for both vertical and horizontal structural

Table 5.2 Damage limits for rapid damage assessment methodology



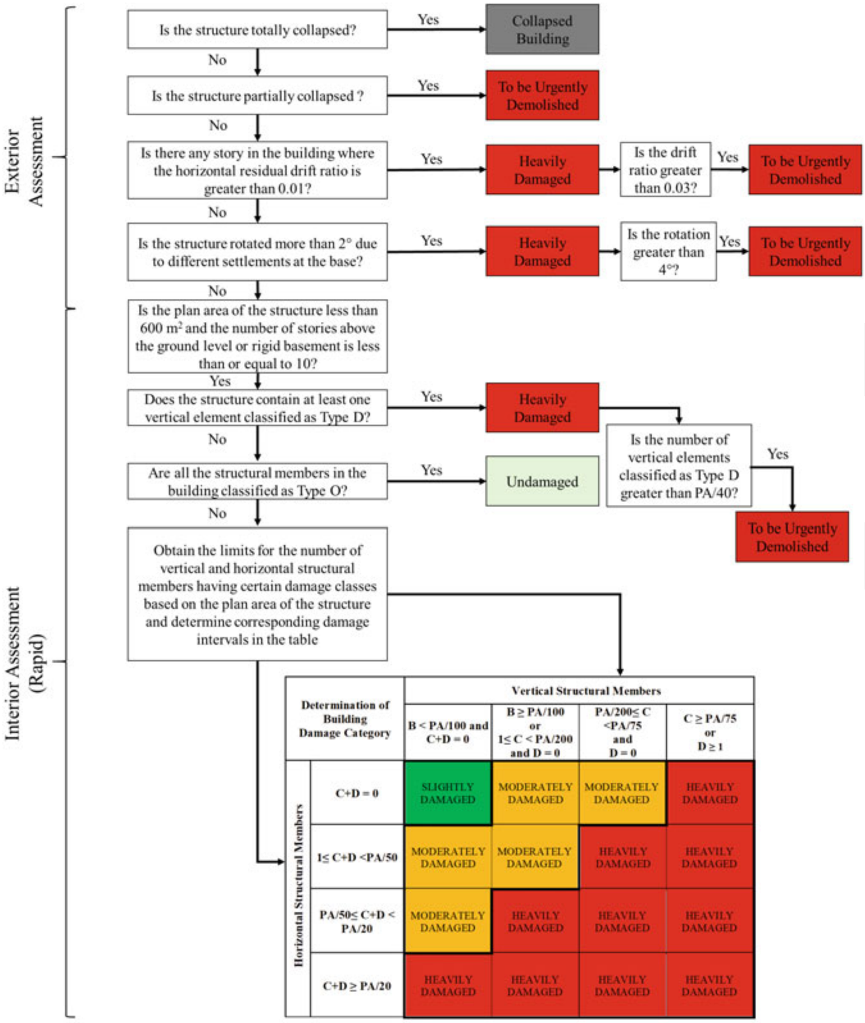
Determination of Building Damage Category		Vertical Structural Members			
		B < PA/100 and C+D = 0	B ≥ PA/100 or 1≤ C < PA/200 and D = 0	PA/200≤ C <PA/75 and D = 0	C ≥ PA/75 or D ≥ 1
Horizontal Structural Members	C+D = 0	SLIGHTLY DAMAGED	MODERATELY DAMAGED	MODERATELY DAMAGED	HEAVILY DAMAGED
	1≤ C+D <PA/50	MODERATELY DAMAGED	MODERATELY DAMAGED	HEAVILY DAMAGED	HEAVILY DAMAGED
	PA/50≤ C+D < PA/20	MODERATELY DAMAGED	HEAVILY DAMAGED	HEAVILY DAMAGED	HEAVILY DAMAGED
	C+D ≥ PA/20	HEAVILY DAMAGED	HEAVILY DAMAGED	HEAVILY DAMAGED	HEAVILY DAMAGED

members and the building damage category is obtained by the intersection of these intervals. The rapid damage assessment algorithm is presented in Fig. 5.7.

Detailed Inspection Procedure

If the subject structure is not suitable for the rapid inspection, the detailed procedure can be applied regardless of limits for the base area or the number of stories of the building. In this examination, Weighted Damage Percentage for Vertical Members (WDPVM) and the number of damaged horizontal members are determined at the inspected story based on the observed damage categories and damage modifiers presented in Table 5.3. More than 100 experimental test results have been exploited in the determination of these factors. For the corresponding damage conditions stated in Table 5.1, the dissipated energies were compared with the total energy dissipation capacity of the specimens. The factors in Table 5.3 represents the ratio of the dissipated energy to the total energy dissipation capacity of the structural members.

The damage level of each vertical structural member is weighted with its cross-sectional area. Accordingly, the calculation of WDPVM is carried out with respect to Eq. (5.1) where O, A, B and C stand for the total cross-sectional area of the vertical members assigned to Type O, Type A, Type B and Type C damage categories, respectively. Since the case of observing at least one vertical member with Type D



Determination of Building Damage Category		Vertical Structural Members			
		B < PA/100 and C+D = 0	B ≥ PA/100 or 1≤ C < PA/200 and D = 0	PA/200≤ C <PA/75 and D = 0	C ≥ PA/75 or D ≥ 1
Horizontal Structural Members	C+D = 0	SLIGHTLY DAMAGED	MODERATELY DAMAGED	MODERATELY DAMAGED	HEAVILY DAMAGED
	1≤ C+D <PA/50	MODERATELY DAMAGED	MODERATELY DAMAGED	HEAVILY DAMAGED	HEAVILY DAMAGED
	PA/50≤ C+D < PA/20	MODERATELY DAMAGED	HEAVILY DAMAGED	HEAVILY DAMAGED	HEAVILY DAMAGED
	C+D ≥ PA/20	HEAVILY DAMAGED	HEAVILY DAMAGED	HEAVILY DAMAGED	HEAVILY DAMAGED

Fig. 5.7 Rapid damage assessment algorithm

Table 5.3 Damage modification factors (λ) for RC elements

Member damage category	Damage modification factor
O	0.00
A	0.20
B	0.40
C	0.70
D	1.00

damage category directly leads the damage assessment procedure to a conclusion where the damage category of the building is determined as either Heavily Damaged or Building to be Urgently Demolished, the vertical members with Type D damage category are excluded in Eq. (5.1). The coefficients (0.20, 0.40 and 0.70) are the damage modification factors (λ) for the corresponding damage categories given in Table 5.3.

$$WDPVM = \frac{A \times 0.20 + B \times 0.40 + C \times 0.70}{O + A + B + C} \times 100 \tag{5.1}$$

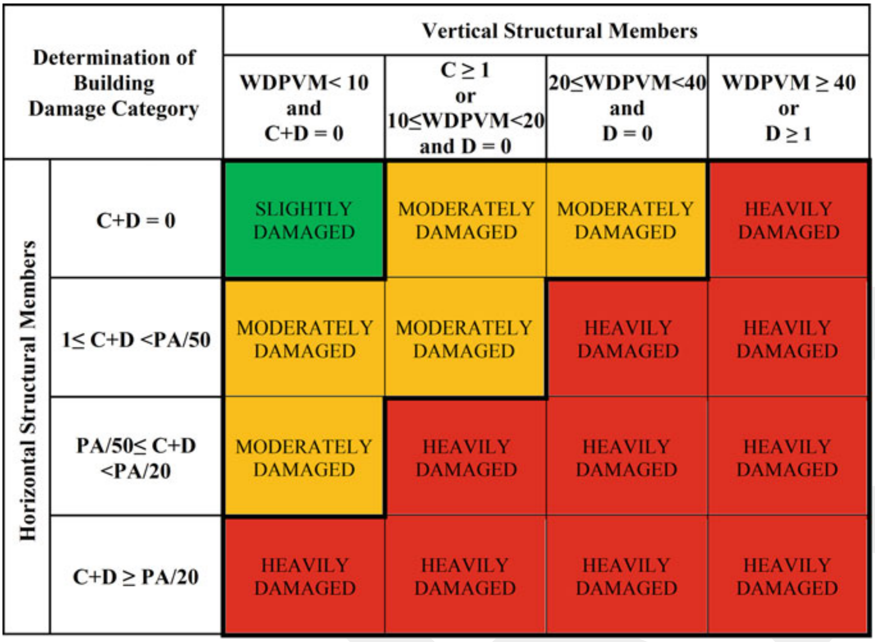
A weighted damage percentage is not calculated for the horizontal structural members because of the practical concerns and the fact that the variations in the beam sizes are considerably low in comparison to that in the vertical members. It is sufficient to determine the number of Type C and Type D members by considering the damage limits defined in Sect. 5.2.2.

The damage category of the inspected building is determined based on the damage categories observed in vertical and horizontal members together with the damage percentage obtained from Eq. (5.1) and the limits that are determined based on the PA of the structure. For vertical and horizontal structural members, the following damage limits are defined for the detailed damage assessment algorithm.

- Damage limits for vertical structural members:
  - The case where WDPVM is less than 10 and no vertical member is categorized as either Type C or Type D
  - The case where WDPVM is greater than or equal to 10 but less than 20 or at least one vertical member is categorized as Type C and no vertical member is classified as Type D
  - The case where WDPVM is greater than or equal to 20 but less than 40 and no vertical member is classified as Type D
  - The case where WDOVM is greater than or equal to 40 or there is at least 1 vertical member classified as Type D.
- Damage limits for horizontal structural members:
  - The case where no horizontal members are categorized as either Type C or Type D
  - The case where the number of horizontal structural members categorized as Type C and Type D is at least one but less than PA/50
  - The case where the number of horizontal members categorized as Type C and Type D is greater than or equal to PA/50 but less than PA/20
  - The case where the number of horizontal members categorized as Type C and Type D is greater than or equal to PA/20.

Similar to the detailed inspection procedure, the building damage category for inspected buildings is obtained by determining the damage intervals for both vertical and horizontal members in accordance with Table 5.4 for both vertical and horizontal

Table 5.4 Damage limits for detailed damage assessment methodology



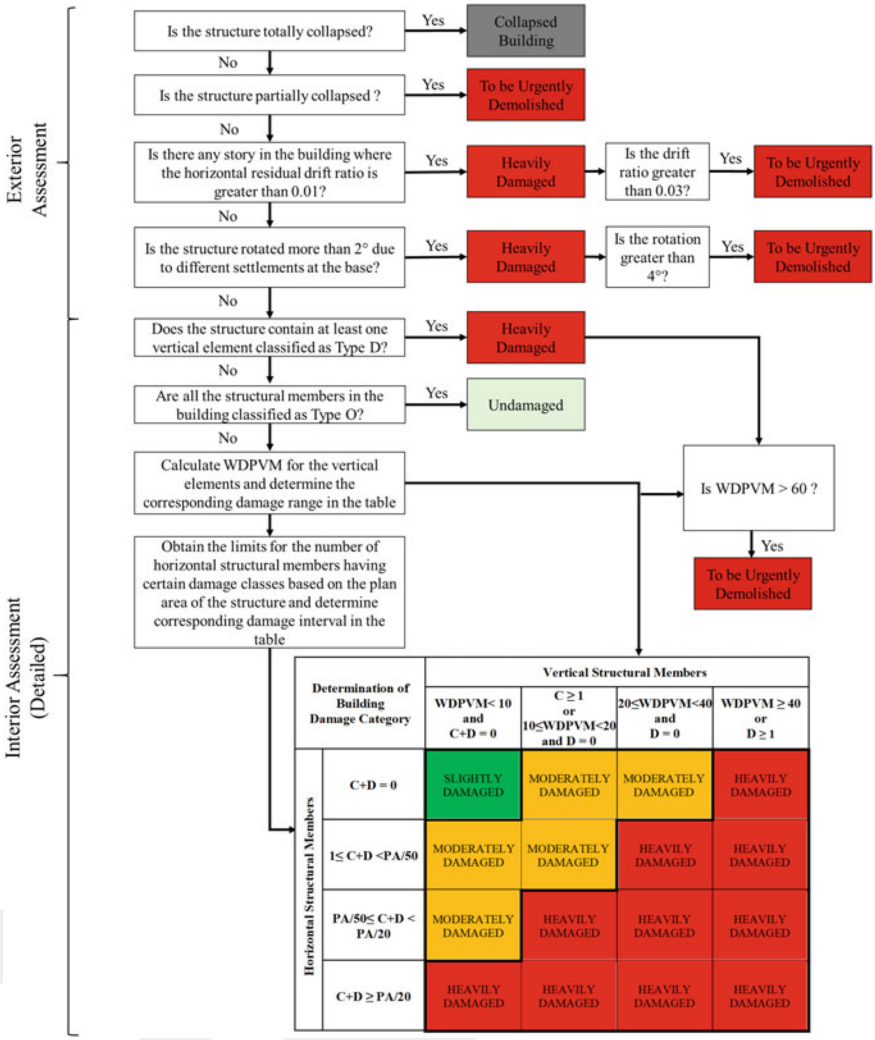
Determination of Building Damage Category		Vertical Structural Members			
		$WDPVM < 10$ and $C+D = 0$	$C \geq 1$ or $10 \leq WDPVM < 20$ and $D = 0$	$20 \leq WDPVM < 40$ and $D = 0$	$WDPVM \geq 40$ or $D \geq 1$
Horizontal Structural Members	$C+D = 0$	SLIGHTLY DAMAGED	MODERATELY DAMAGED	MODERATELY DAMAGED	HEAVILY DAMAGED
	$1 \leq C+D < PA/50$	MODERATELY DAMAGED	MODERATELY DAMAGED	HEAVILY DAMAGED	HEAVILY DAMAGED
	$PA/50 \leq C+D < PA/20$	MODERATELY DAMAGED	HEAVILY DAMAGED	HEAVILY DAMAGED	HEAVILY DAMAGED
	$C+D \geq PA/20$	HEAVILY DAMAGED	HEAVILY DAMAGED	HEAVILY DAMAGED	HEAVILY DAMAGED

structural members. The building damage category is obtained by the intersection of these intervals. The detailed damage assessment algorithm for reinforced concrete structures is outlined in Fig. 5.8.

5.3 Case Study: Assessment of a Structure Damaged After 1999 Kocaeli Earthquake

An earthquake damaged structure investigated after the 1999 Kocaeli earthquake is re-evaluated according to TCIP-DAM-2020 method presented above. The details about the structure, location and observed damages are obtained from the earthquake report prepared by Architectural Institute of Japan in 2001 (AIJ/JSCE/JGS 2001). The building consisted of six stories and was made of reinforced concrete vertical and horizontal structural members. The building was located in Degirmendere district of Kocaeli and was under construction when the earthquake struck.

The structural system of the building did not exhibit partial or total collapse after the earthquake. However, many of the infill walls in the structure were heavily damaged. The walls on the cantilever beams were constructed with AAC blocks and the rest of the infills were built with hollow clay bricks. General views of the structure after the earthquake are shown in Fig. 5.9. The outer dimensions of the structure are

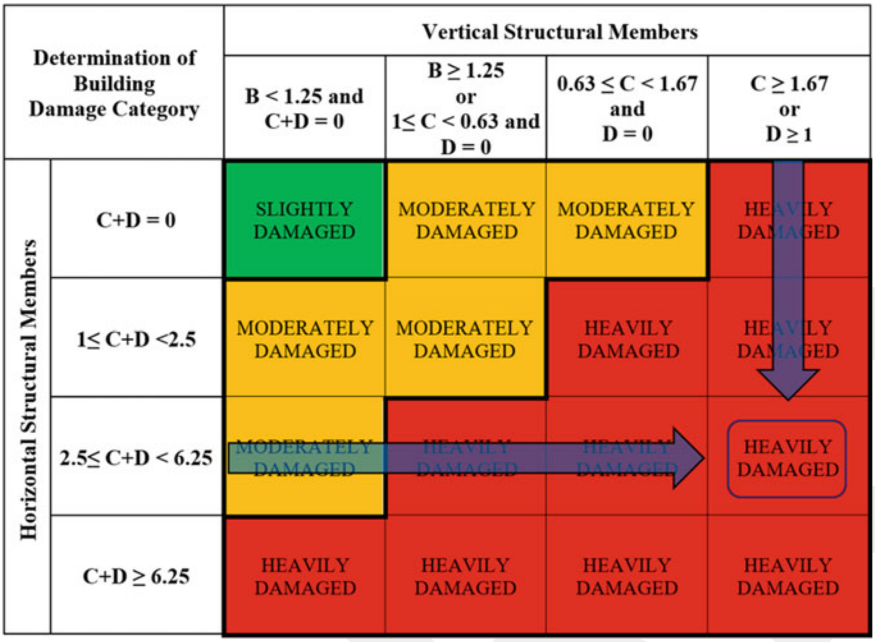


Determination of Building Damage Category		Vertical Structural Members			
		WDPVM< 10 and C+D = 0	C ≥ 1 or 10≤WDPVM<20 and D = 0	20≤WDPVM<40 and D = 0	WDPVM ≥ 40 or D ≥ 1
Horizontal Structural Members	C+D = 0	🟩 SLIGHTLY DAMAGED	🟨 MODERATELY DAMAGED	🟨 MODERATELY DAMAGED	🟥 HEAVILY DAMAGED
	1≤ C+D <PA/50	🟨 MODERATELY DAMAGED	🟨 MODERATELY DAMAGED	🟥 HEAVILY DAMAGED	🟥 HEAVILY DAMAGED
	PA/50≤ C+D < PA/20	🟨 MODERATELY DAMAGED	🟥 HEAVILY DAMAGED	🟥 HEAVILY DAMAGED	🟥 HEAVILY DAMAGED
	C+D ≥ PA/20	🟥 HEAVILY DAMAGED	🟥 HEAVILY DAMAGED	🟥 HEAVILY DAMAGED	🟥 HEAVILY DAMAGED

Fig. 5.8 Detailed damage assessment algorithm

11.6 and 11.4 m in X and Y directions, respectively. The PA of the structure is approximately 125 m^2. The plan view of the first story of the structure is shown in Fig. 5.10. The report (AIJ/JSCE/JGS 2001) stated that typical columns have 250 × 500 mm cross-section dimensions and have 8 longitudinal reinforcing bars with a diameter of 16 mm, which corresponds to 1.29% of a longitudinal reinforcement ratio. No information was given regarding stirrup diameter, spacing and hook details. Typical beams in the building have 200 × 500 mm cross-section dimensions. It was stated that bars with diameters of 12 and 14 mm were used as longitudinal reinforcements in the beams together with 6 mm stirrups with a spacing of 250 mm.

Table 5.5 Damage limits obtained for the case study structure



Determination of Building Damage Category		Vertical Structural Members			
		B < 1.25 and C+D = 0	B ≥ 1.25 or 1≤ C < 0.63 and D = 0	0.63 ≤ C < 1.67 and D = 0	C ≥ 1.67 or D ≥ 1
Horizontal Structural Members	C+D = 0	SLIGHTLY DAMAGED	MODERATELY DAMAGED	MODERATELY DAMAGED	HEAVILY DAMAGED
	1≤ C+D <2.5	MODERATELY DAMAGED	MODERATELY DAMAGED	HEAVILY DAMAGED	HEAVILY DAMAGED
	2.5≤ C+D < 6.25	MODERATELY DAMAGED	HEAVILY DAMAGED	HEAVILY DAMAGED	HEAVILY DAMAGED
	C+D ≥ 6.25	HEAVILY DAMAGED	HEAVILY DAMAGED	HEAVILY DAMAGED	HEAVILY DAMAGED

Fig. 5.9 Views of the building; **a** Western side; **b** Southwestern side (Modified from AIJ/JSCE/JGS 2001)

(a) (b)

The plan area of the structure is smaller than 600 m^2 and the number of stories above the ground level is less than or equal to 10. Hence the damage assessment can be executed by following the rapid evaluation algorithm.

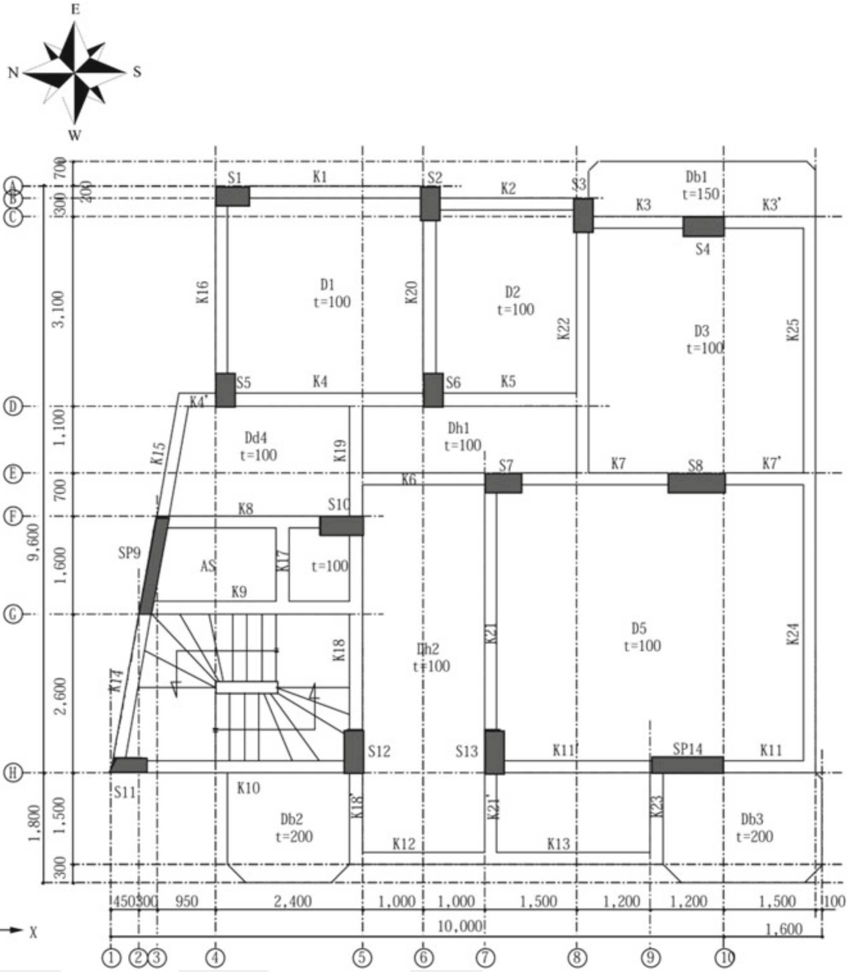


Fig. 5.10 Plan view of the evaluated building (AIJ/JSCE/JGS 2001) (mm)

Exterior Assessment

As shown in Fig. 5.7, the evaluation procedure starts with exterior assessment. The structure did not exhibit partial or total collapse and a residual drift that is greater than 1%. Also, no rigid rotation at the base that is greater than 2° was observed. The answer to these steps stated in the exterior assessment is ‘No’, hence the building damage category cannot be obtained as Heavily Damaged or Building to be Urgently Demolished from the exterior assessment phase. Thus, the damage assessment procedure continues with the interior assessment.

Interior Assessment

The interior assessment begins at the most damaged story in the building, which in this case is the first floor. After Kocaeli (1999) earthquake, the post-earthquake damage assessment of the structure was carried out according to the 1991 version of the Japanese damage assessment guideline (Japan and building disaster prevention association (JBDPA) 2015), which was in force at that time in Japan. The 2015 version of the guideline (Japan and building disaster prevention association (JBDPA) (2015) evaluates the post-earthquake condition of buildings considering total collapse mechanism where damages in both columns and beams are considered. Conversely, the 1991 version assumed soft-story collapse mechanism which only took into account the degradations in the shear strength of the vertical members.

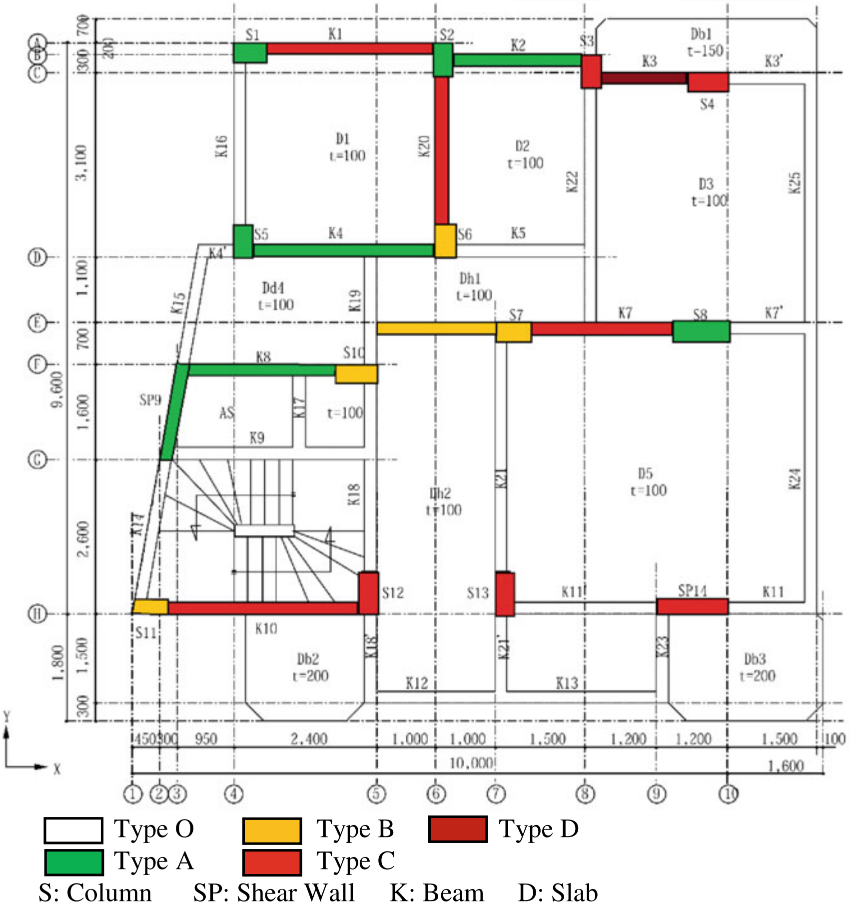
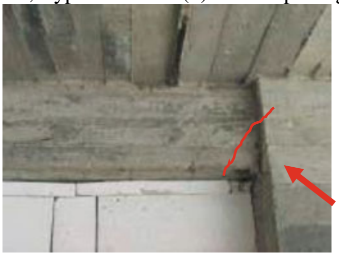


Fig. 5.11 Damaged structural members in the first story (mm) (Modified from (AIJ/JSCE/JGS 2001)

The earthquake report (AIJ/JSCE/JGS 2001) did not state the detailed damages for all elements (i.e. residual crack width, crushing of cover concrete, etc.), instead, the damage categories of vertical and horizontal structural members which were assigned in accordance with the 1991 Japanese method (Japan and building disaster prevention association (JBDPA) 2015) were given. By considering the member damage categories defined in the Japanese method (Japan and building disaster prevention association (JBDPA) 2015) and TCIP-DAM-2020 (Table 5.1), the reported member damages were converted to the corresponding member damage categories defined in TCIP-DAM-2020 method. The vertical and horizontal structural members with different damage categories are emphasized with different colors on the plan view of the first story shown in Fig. 5.11. The representative photos of the structural damages observed in the vertical and horizontal members are presented in Fig. 5.12.

No vertical structural members are categorized as Type D; therefore, the building cannot be directly categorized as Heavily Damaged. Also, because of the existence of damaged structural members, the structure cannot be directly categorized as Undamaged. Hence, the damage category is determined via the number limits defined for structural members with certain damage categories (Table 5.2). In the first story, five vertical members are categorized as Type C and the total number of horizontal elements categorized as Type C and Type D is five. Based on the PA of the structure (125 m^2) the limits for the number of damaged vertical and horizontal members are presented in Table 5.5. The number of vertical members with Type C damage category is greater than 1.67 and the number of horizontal members with Type C and Type D damage category is between 2.5 and 6.25. By intersecting the corresponding damage

(a) Cover spalling in SP14, Type C (b) Cover spalling in S12, Type C



(c) Shear crack and cover spalling in K7, Type C

Fig. 5.12 Damaged members (Modified from (AIJ/JSCE/JGS 2001) intervals determined for vertical and horizontal members, the damage assessment performed according to TCIP-DAM-2020 is concluded by categorizing the building as ‘Heavily Damaged’. After the earthquake, the building was categorized as ‘Very Heavy Damage’ according to the 1991 version of the Japanese guideline (Japan and building disaster prevention association (JBDPA) 2015). Also, at that time, the building was evaluated based on EMS-98 (Grünthal 1998) as well. The damage grade of the structure by this code was ranked as Damage Grade 3 which corresponds to ‘Substantial to Heavy Damage’.

5.4 Concluding Remarks

In this paper, the general framework of the new version of the damage assessment algorithm developed for TCIP is presented (TCIP-DAM-2020). In the development of rapid and detailed assessment algorithms, the observations gained through the execution of 200 numeric structural performance analyses and 80,000 repair cost analyses are considered. Also, the results of more than 100 experimental tests obtained from the literature have been benefitted to determine the modification factors that represent the behavior of earthquake-damaged structural members.

One of the most important improvements in the new algorithm is the enlargement of the application area of the rapid assessment method so that the method can be applied to the majority of the building stock in Turkey. This method enables the determination of the building damage category based on the number of damaged vertical structural members and the plan area of the inspected structure without calculating damage percentages for vertical members. If a damaged structure does not fulfill the geometric limitations defined in the rapid assessment method, the detailed method is implemented. Also, in the new version, both in rapid and detailed methods, if the building has at least one vertical member with Type D damage category, the building damage class can be easily determined as Heavily Damaged or Building to be Urgently Demolished. With TCIP-DAM-2020, the damage assessment applications are envisioned to be carried out in a much quicker way which would enable the inspectors to evaluate more earthquake-damaged structures in a certain time period. Considering the number of buildings in need of damage inspection and the lack of qualified personnel after earthquakes, this is deemed to be the most beneficial feature of TCIP-DAM-2020.

Another significant improvement in the new version of the damage assessment algorithm for RC structures is the inclusion of the damages that take place in the horizontal structural members in the determination of building damage category. This is especially beneficial for the post-earthquake damage assessment of code-complying structures whose portion in the building stock is constantly increasing due to the transformation of cities. All in all, the new damage assessment algorithm which is based on a broad scientific background and experimental and numerical analyses will enable quicker post-earthquake damage assessments without any compromise in objectivity and reliability.

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