Evaluation of the Relationship Between Seismic Damage and Structural Properties of Existing RC Buildings

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SUMMARY
This study aims to evaluate the relationship between seismic damage and structural properties of existing RC buildings. For this purpose, a detailed investigation on the buildings that are damaged after 19 May 2011 Simav (Turkey) Earthquake is carried out. Total of 144, buildings are carefully examined for the properties of structural system (sizes of structural elements, walls, lateral and longitudinal reinforcements of RC members, etc.), architectural layout, damage conditions, concrete strength, and soil conditions. In addition, seismic performance of these buildings are tried to be estimated with 3 different rapid evaluation methods. The properties of the buildings expected to be highly correlated with seismic damage are evaluated. It is found that, especially for smaller seismic events, the damage state may be highly dependent on local modes regardless of general building properties.

Keywords: earthquake, existing building, rapid seismic evaluation, reinforced concrete, seismic damage.

1. INTRODUCTION
An earthquake with a magnitude of 5.7 (ML) has struck Simav, Kutahya located in the western part of Turkey on May 19, 2011 at 20:15 (GTM). The earthquake indirectly caused 3 casualties and more than 70 injuries. The epicentral coordinates of the earthquake are 39.1328 N – 29.0820 E with focal depth 24.46 km as reported by Disaster and Emergency Management Presidency, Earthquake Department(AFAD, 2011a). The depth and magnitude is given as 10 km and 5.7, respectively by the Kandilli Observatory (KOERI, 2011) while USGS has given the depth as 9 km and magnitude as 5.8 (USGS, 2011). The epicenter is at the northeast of the Simav district with a distance of 13 km, near Sogut village. Simav earthquake has reported to have a normal fault mechanism. The earthquake region is at seismic zone 1 of Turkey, which is the most critical among 4 seismic zones (TEC, 2007). The ground motion has been strongly felt by approximately 135,000 people and caused observable damage around a maximum of 25 km radius from the epicenter. Although the magnitude of earthquake is moderate, the effects of the earthquake on the structures are serious. The number of damaged and collapsed buildings around Simav is given in Table 1.1 (AFAD, 2011b).

Table 1.1. The number of the damaged and collapsed buildings (AFAD, 2011b)

<table>
<thead>
<tr>
<th>Region</th>
<th>Collapsed</th>
<th>Heavy</th>
<th>Moderate</th>
<th>Light</th>
<th>None</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simav City</td>
<td>5</td>
<td>331</td>
<td>261</td>
<td>1531</td>
<td>2265</td>
</tr>
<tr>
<td>Simav Towns</td>
<td>41</td>
<td>484</td>
<td>74</td>
<td>1861</td>
<td>2658</td>
</tr>
<tr>
<td>Simav Villages</td>
<td>63</td>
<td>445</td>
<td>51</td>
<td>898</td>
<td>596</td>
</tr>
<tr>
<td>Hisarcık*</td>
<td>3</td>
<td>79</td>
<td>6</td>
<td>337</td>
<td>64</td>
</tr>
<tr>
<td>Şaphane*</td>
<td>2</td>
<td>46</td>
<td>7</td>
<td>290</td>
<td>153</td>
</tr>
<tr>
<td>Pazarlar*</td>
<td>1</td>
<td>56</td>
<td>10</td>
<td>255</td>
<td>43</td>
</tr>
</tbody>
</table>

*Total of all residential units in the district
This study aims to evaluate the relationship between seismic damage and structural properties of existing RC buildings. For this purpose a detailed investigation on the buildings that are damaged after 19 May 2011 Simav (Turkey) Earthquake is carried out. Total of 144 buildings are carefully examined for the properties of structural system (sizes of structural elements, walls, lateral and longitudinal reinforcements of RC members, etc.), architectural layout, damage conditions, concrete strength, and soil conditions. Concrete core samples are taken from all the buildings and Standard Penetration Tests, and MASW-(Multi-channel Analysis of Surface Waves) tests are performed for determination of soil conditions.

In addition, seismic performance of these buildings are tried to be estimated with 3 different rapid evaluation methods as: Yakut (2004), Ozcebe (2004) and P25 (Bal et al., 2006). Relation between damage state of the buildings and the scores of the rapid screening methods are investigated. And, the key features of the buildings that are strongly correlated with seismic damage are tried to be pointed out.

Evaluations based on the relations between observed damage, rapid evaluation method scores, structural and other properties of the buildings are made. The outcomes may be useful for seismic risk assessment and mitigation studies.

2. SEISMIC DAMAGES IN THE REGION AND EVALUATIONS

Even if the earthquake may not be taken as a large one, it led to widespread and significant damages on structures. The number of damaged buildings is given in Table 1.1. Information on the seismic damages in the region can be found in some studies (Inel et al., 2012).

2.1. Seismic Damages In Simav City

The numbers of damaged reinforced concrete buildings in Simav city with different number of stories are given in Table 2.1 and the ratios of the damaged buildings to the total number of RC buildings are given in Figure 2.1. In the figure, the gray values are the ratio of the buildings with moderate, heavy damage and collapse to the total number of buildings with corresponding number of story and the dark values are the ratio for the heavy damage and collapsed buildings.

<table>
<thead>
<tr>
<th>Story #</th>
<th>Undamaged</th>
<th>Slight</th>
<th>Moderate</th>
<th>Heavy</th>
<th>Collapsed</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>343</td>
<td>56</td>
<td>22</td>
<td>1</td>
<td>0</td>
<td>422</td>
</tr>
<tr>
<td>2</td>
<td>192</td>
<td>46</td>
<td>5</td>
<td>1</td>
<td>0</td>
<td>244</td>
</tr>
<tr>
<td>3</td>
<td>234</td>
<td>120</td>
<td>15</td>
<td>7</td>
<td>0</td>
<td>376</td>
</tr>
<tr>
<td>4</td>
<td>201</td>
<td>170</td>
<td>47</td>
<td>25</td>
<td>0</td>
<td>443</td>
</tr>
<tr>
<td>5</td>
<td>145</td>
<td>146</td>
<td>67</td>
<td>14</td>
<td>0</td>
<td>372</td>
</tr>
<tr>
<td>6</td>
<td>58</td>
<td>108</td>
<td>24</td>
<td>6</td>
<td>0</td>
<td>196</td>
</tr>
<tr>
<td>7</td>
<td>4</td>
<td>13</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>22</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>23</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>23</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>1177</td>
<td>683</td>
<td>183</td>
<td>55</td>
<td>1</td>
<td>2099</td>
</tr>
</tbody>
</table>

As seen in the figure, damage level increases with increasing number of story resembling the case after many other earthquakes in Turkey (Sezen et al., 2003; Dogangun, 2004, Kaplan et al., 2004; Inel et al., 2008a; Inel et al., 2008b). This is evident especially for the series including moderate and higher damage levels (gray color). Nevertheless, for the large damage levels, heavy and collapsed buildings, ratio of the buildings increases up to four story ones and decreases afterwards if the seven story ones are not considered. High ratio for the seven story ones may be attributable to the few number of buildings resulting in high ratio for even two damaged ones. Low damage ratios for the eight story buildings support this interpretation. In addition, since there is only one nine-story building, it cannot
be taken into consideration.

The higher damage level for 4-5 story buildings is also a shared conclusion with other theoretical studies and reconnaissance reports after earthquakes (Akkar et al., 2005; Inel et al., 2008b). This may be a result of closer period values with soil and lower quality of construction at these buildings when compared to higher story ones (Inel et al., 2008a).

![Figure 2.1. Ratios of the damaged RC buildings in Simav city to the total number of buildings for different number of stories](image)

2.1. Building Set

The set includes more than 220 buildings but only reinforced concrete ones will be included in scope of the paper which consists of 144 buildings. RC buildings are carefully examined for the properties and geometry of structural system, sizes of structural elements and infill walls at ground story. Damage states of the buildings are graded according to Classifications used in the European Macroseismic Scale (EMS) (EMS98, 1998). Decisions on the damages at the member level is done according to Quick Inspection Manual of Damaged Reinforced Concrete Buildings due to Earthquakes which is in compliance with RC building damages in Turkey (Kaminosono, 2002). However to have a better evaluation, the damage state steps in EMS are further classified in two. The damage states in EMS are in 5 grades and it is modified to be in 9 with an addition of 0.5 steps. Definition of EMS and Modified EMS (used in this paper) grades are given in Table 2.2. The distribution of the damaged buildings according to Modified EMS classification among all the examined buildings is given in Figure 2.2.

<table>
<thead>
<tr>
<th>EMS</th>
<th>Modified EMS</th>
<th>Structural</th>
<th>Non-Structural</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade1</td>
<td>Grade1</td>
<td>None</td>
<td>Slight</td>
</tr>
<tr>
<td>Grade2</td>
<td>Grade1.5</td>
<td>None</td>
<td>Slight to Moderate</td>
</tr>
<tr>
<td>Grade2</td>
<td>Grade2</td>
<td>Slight</td>
<td>Moderate</td>
</tr>
<tr>
<td>Grade2</td>
<td>Grade2.5</td>
<td>Slight to Moderate</td>
<td>Moderate to Heavy</td>
</tr>
<tr>
<td>Grade3</td>
<td>Grade3</td>
<td>Moderate</td>
<td>Heavy</td>
</tr>
<tr>
<td>Grade3</td>
<td>Grade3.5</td>
<td>Moderate to Heavy</td>
<td>Moderate to Heavy</td>
</tr>
<tr>
<td>Grade4</td>
<td>Grade4</td>
<td>Heavy</td>
<td>Very Heavy</td>
</tr>
<tr>
<td>Grade4</td>
<td>Grade4.5</td>
<td>Heavy to Very Heavy</td>
<td>Partial Collapse</td>
</tr>
<tr>
<td>Grade5</td>
<td>Grade5</td>
<td>Collapse</td>
<td>-</td>
</tr>
</tbody>
</table>

Another important parameter about the buildings that may be point of interest is the compressive concrete strength of the buildings. The in-place concrete strengths are calculated as mean value minus standard deviation. The in-place concrete strengths of the buildings are given in Figure 2.3 and the distribution is given in Figure 2.4. As can be seen in the figures concrete strength values are low. More
than %17 of them are even below 5.0 MPa and values even below 4.0 MPa is encountered. It is expected as they are selected among the buildings that are damaged after such a moderate earthquake.

![Figure 2.2](image)

**Figure 2.2.** The ratios of the damaged buildings according to Modified EMS classification

![Figure 2.3](image)

**Figure 2.3.** The ratios of the damaged buildings according to Modified EMS classification

![Figure 2.4](image)

**Figure 2.4.** The distribution of in-place concrete strengths of the investigated buildings

### 2.3. Evaluations On The Reasons Of The Damage

The relation between certain parameters of the buildings and damage state are investigated. The parameters selected are number of stories, column area over building area, compressive concrete
strength, amount of transverse reinforcement, infill-wall area over building area and shear wave velocity (Vs) representing the soil conditions. In Figure 2.5, the relation between damage and mentioned parameters are given. In the figures, it should be noted that single dot might represent more than one building since many of them may share the same or close values of the considered parameter.

As can be seen on the figure correlation factor of the given 6 parameters are between 0.16 and 0.01 does not indicate remarkable connection. Although each parameter is not well associated with damage, it is examined if the combination of these may have good correlation. Equations including combinations of the given parameters are investigated for minimum error with the EMS score. The maximum correlation coefficient obtained is 0.38 including all the parameters. As it is not the main subject of the paper and the gathered results are in well agreement with the single parameter attempts, optimization with classical solver capabilities in Excel is assumed enough.

The correlation factor may be assumed as very low because it is optimized especially for the given building set after a certain earthquake. This may be taken as an indicator that the considered building properties are not enough to establish a strong relation between damage. The details are explained later in the following.

2.4. Correlation Between Damage Score And Rapid Evaluation Methods

The performance of the rapid screening methods after this earthquake may be a point of subject. The correlation between the damage and screening methods are given in Figure 2.6. The damage of the buildings seems to be decreasing with increasing scores as expected but with low correlation factors. The maximum correlation factor is for Ozcebe (2004) method with a value of 0.28. The others are 0.12 and 0.11 for Yakut (2004) and P25 methods, respectively. The scatters from the trendlines are considerable for all of them and the outcome may not be seen as satisfactory.

As the scope of the study and the lower magnitude of the Simav earthquake are considered, the outcomes of this study do not suggest which of these methods have greater accuracy. The authors also want to clarify the point that they do not imply that the rapid screening methods are useless or fails to estimate seismic damage accurately. On the contrary, they think that these methods are important steps towards the estimation of damages for stock of buildings in a practical way. The evaluation of the strong and weak points of the rapid screening methods and when to use them safely are among the aims of this paper. This way authors try to contribute and encourage the development of these methods.

The second subject of concern may be how the considered rapid evaluation methods are related, if the values of the scores of these methods are in accordance with each other. In Figure 2.7, the correlations between the couples of the rapid screening methods are given. The correlation factors again happen to be low, between 0.24 and 0.29.

The low correlation may be expected when the differences in the methods are considered. For example, the concrete strength is crucial for the Yakut (2004) as it directly affects the Capacity Index. However, for the P25 method it only effects one of the P scores among seven one, as being one of the other 14 “f factors” that affects the same P score. In Ozcebe (2004) method, it is not considered at all. Same is also true for the amount of lateral reinforcement. It is not considered in Yakut (2004) and Ozcebe (2004) methods but, a parameter in P25 method like concrete strength. Even if they all has the same goal: rapid assessment of RC buildings, they handle the problem very differently. Many other important divergences may be found between these methods.

Although the correlation factors are low, when the figures are examined carefully, they do not look to be much unrelated, except some points that are very different from the trendlines. In all figures, correlation factors are greatly reduced by these points. These figures belong to the buildings, properties of which are handled differently in the methods.
2.5. The Reasons Of Low Correlation Between Building Parameters And Rapid Screening Methods

The low correlation of the building damage with the given parameters is a considerable outcome. Authors think the reason for that is the member level shear damage at the structural elements of the buildings. The considered properties of the buildings can be effective on the behavior, if the buildings behave as a system. Otherwise, the parameters will not be meaningful. The single way of RC buildings behaving as a system is the flexure. In flexure, the ductility is possible and seismic forces are distributed among structural elements. However, in shear behavior, members are failed in early stages of the ground motion and system integrity cannot be achieved. Members in shear may be significantly damaged even if the other parts of the building are in much lesser damage levels, making the damage distribution uneven and more complicated.

In the investigated set, damage states of the significant amount of the buildings are determined based on the shear cracks, especially for the ones with moderate and heavier damage states. One may argue that the buildings with shear behaviour may be identified by the concrete strength and lateral reinforcement amount considered above. Therefore, correlation can still expected to be higher. In determination of whether a member behaves in shear or flexure, one of the important parameters is the clear length. The clear length of members in buildings may greatly vary depending on the architectural layout. Columns beside windows or other openings may become short columns. In addition, as pointed out in literature accidental short columns may arise due to partial disintegration of infill walls (Inel et al., 2012). Beams may also suffer the shear damage due to partial or orthogonal walls along their length. When the concrete strength and lateral reinforcement amount in the building set are considered, the members are in the gray area between shear and flexure. Small changes may have important results. Consequently, determination of behavior of RC members solely with concrete strength and lateral reinforcement amount is not an easy task.

As the damage states are determined according to the cracks, whether the reasons of them are related with the building properties is very important. The damages due to flawed constructions like reinforcement detailing mistakes, cold joint cracks because of insufficient cleaning for foreign substances, not enough wetting or over wetting between consecutive concrete pourings and damages due to overhangs cannot be identified considering general building characteristics. These kinds of damages are reported in the area (Inel et al., 2012).

Furthermore, actual damage levels of the buildings after earthquakes are also related with their neighbouring conditions. The middle buildings in a series confined by other buildings may take lesser damage or the ones (especially at the end) suffered from pounding may take more damage (Inel and Ozmen, 2006) compared to the standalone case as assumed in many damage estimation methodologies (Ozczebe, 2004; Yakut 2004).

It seems that as the local damage modes increase, and the damage levels spread in a wide range due to the lower magnitude of the earthquakes; the estimations with the rapid screening method may diverge from the actual scene after earthquake.
Figure 2.5. Relation between certain parameters of the buildings and damage state: (a) number of stories (b) column area over building area ratio (c) compressive concrete strength (d) amount of transverse reinforcement (e) infill-wall area over building area (f) shear wave velocity at top 30 m of soil and (g) is the estimation of the modified EMS score.
Figure 2.6. The Relation between damage and considered rapid screening methods: (a) Ozcebe (2004) (b) Yakut (2004) and (c) P25 method


3. SUMMARY AND CONCLUSIONS

Evaluations based on the relations between observed damage, rapid evaluation method scores, structural and other properties of the buildings are made. The findings are summarized in the following:

- When the estimated values of the PGA and acceleration spectrum in Simav are considered, the earthquake might be taken as a moderate one, at most.
- If low damage states are included, damage levels are found to be increasing with increasing number of stories. This resembles the case after many other earthquakes in Turkey (Sezen et
However, for the large damage levels (heavy and collapsed buildings) ratio of the buildings increases up to four story ones and decreases afterwards. The higher damage level for 4-5 story buildings is also a shared conclusion with other theoretical studies and reconnaissance reports after earthquakes (Akkar et al., 2005; Inel et al., 2008b). This may be a result of closer period values with soil and lower quality of construction at these buildings when compared to higher story ones (Inel et al., 2008a).

The damage states of the elaborately investigated building set are mostly in grade 2 to 4 according to EMS98. More than %17 of the in-place concrete strengths of the buildings are even below 5.0 MPa and values even below 4.0 MPa is encountered. It is expected as they are selected among the buildings that are damaged after such a moderate earthquake.

The relation between number of stories, column area over building area, compressive concrete strength, amount of transverse reinforcement, infill wall area over building area and Vs representing the soil conditions and damage state are investigated. The correlation factor of the given parameters are found to be between 0.16 and 0.01, which does not indicate remarkable connection.

Equations including combinations of the given parameters are investigated for minimum error with the EMS score. The maximum correlation coefficient obtained is 0.38 including all the parameters.

This may be taken as an indicator that the considered building properties are not enough to establish a strong relation between damage. Authors think the reason for that are the local damages at the structural elements regardless of the building properties. As the damage states are determined according to the cracks, whether the reasons of them are related with the building properties is very important. The damages due to short column or beams, flawed constructions like reinforcement detailing mistakes, cold joint cracks and damages due to overhangs cannot be identified considering general building characteristics. These kinds of damages are reported in the area (Inel et al., 2012).

The damage of the buildings seems to be decreasing with increasing rapid screening method scores as expected but with low correlation factors. The maximum correlation factor is for Ozcebe (2004) method with a value of 0.28. The others are 0.12 and 0.11 for Yakut (2004) and P25 methods, respectively.

The authors do not imply that the rapid screening methods are useless or fails to estimate seismic damage accurately. On the contrary, they think that these methods are important steps towards the estimation of damages for stock of buildings in a practical way. The evaluation of the strong and weak points of the rapid screening methods and when to use them safely are among the aims of this paper. This way authors try to contribute and encourage the development of these methods.

The severity of the seismic action may also be very important for the low relation with considered parameters. Since the earthquake is not a large one, building damages after Simav earthquake seem to be spread in a wide range. And, according to the positive or negative effects of the mentioned factors, buildings may be in one damage state or another. If the earthquake had been a large one, it would collapse or heavily damage all the flawed buildings, making them in the same damage group. Since the better ones are more likely to be behave in flexure the building properties will be more representative regarding the damage state.

The correlations between the rapid screening methods are also investigated. The correlation factors for couples of them are also low, between 0.24 and 0.29. The low correlation may be expected when the differences in the methods are considered. Even if they all has the same goal: rapid assessment of RC buildings, they handle the problem differently.

Although the correlation factors are low, when examined carefully, do not look to be much unrelated, except for some buildings that have very different scores in each of the methods. The correlation factors are greatly reduced by these.

The study is actually planned to evaluate the building damage data after 19 May 2011 Simav earthquake and determine the factors that are highly correlated with seismic damage with the elaborately examined building set. The correlation factors generally happened to be low and lead to
conclusion that assessment of seismic event are very complex and local damage modes are very important for the estimation of actual scene after earthquake.

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