Chapter 10
Earthquake Physical Risk/Loss Assessment Models and Applications: A Case Study on Content Loss Modeling Conditioned on Building Damage

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Abstract This paper presents a novel approach to develop content fragility conditioned on building damage for contents used in residential buildings in Turkey. The approach combines the building damage state probabilities with the content damage probabilities conditioned on building damage states to develop the content fragilities. The paper first presents the procedure and then addresses the epistemic uncertainty in building and content fragilities to show their effects on the content vulnerability. The approach also accounts for the expert opinion differences in the content replacement cost ratios (consequence functions) as part of the epistemic uncertainty. Monte Carlo sampling is used to consider the epistemic uncertainty in each model component contributing to the content vulnerability. A sample case study is presented at the end of the paper to show the implementation of the developed content fragilities by calculating the average annual loss ratio (AALR) distribution of residential content loss over the mainland Turkey.

10.1 Introduction

Porter (2019) defines probabilistic seismic risk as the relationship between the rate (or probability) of an undesirable outcome (e.g., structural collapse, business interruption) and a measurable metric (e.g., money) to quantify the undesirable outcome. The components involved in risk assessment are:

(a) the target exposure: a single asset or an inventory located at a specific site or a region,

(b) the seismic hazard: explaining the exceedance frequency of the ground-motion intensity measure (GMIM) used in defining the conditional probability of the undesirable outcome and,

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(c) the fragility function: describing the occurrence probability of the undesirable outcome conditioned on the GMIM utilized in quantifying the seismic hazard.

When fragility functions conditioned on the ground-motion metric are combined with the consequence models, we quantify the loss (repair costs, loss of functionality). The functions measuring the loss in terms of GMIM is referred to as vulnerability functions or vulnerability models. The above terminology can be found in most of the modern seismic risk assessment text books (e.g., McGuire 2004).

One of the probabilistic risk metrics used in insurance and reinsurance is the average annual loss (AAL) that measures the expected annual loss over a predefined range of GMIM with different exceedance frequencies (Eq. 10.1). If, for example, the loss is measured in terms of repair cost, AAL is the average money that would be spent every year to repair the asset. To this end, $y(s)$ in Eq. (10.1) is the vulnerability function in terms of GMIM, s, and the derivative of the seismic hazard curve $G(s)$ represents the annual probability producing exactly s. The negative sign accounts for the negative slope of $G(s)$ at s since the hazard curve slopes down to the right at all values of s indicating lower exceedance frequency of higher shaking.

$$AAL = \int_{s=0}^{\infty} y(s) \frac{-dG(s)}{ds} ds \qquad (10.1)$$

Equation (10.2) shows the vulnerability function computation, as described in the HAZUS report (FEMA 2003), by considering the fragility functions providing damage probabilities at different damage states ($\Pr(DS = ds_i)$, $i = 1,\ldots,n$; n is the total number of damage states). The variable RC^{ds_i} is the replacement cost corresponding to $DS = ds^i$. The replacement costs are the monetary losses, representatives of different damage levels and are, therefore, called as consequence functions (or models). The vulnerability function developed by Eq. (10.2) is called as compound loss function in the HAZUS report since it accounts for all possible damage states, proportional to their occurrence probabilities, that the asset can experience during an earthquake.

$$\begin{aligned} y(s) = {} & RC^{ds_1} \cdot \Pr(DS = ds_1) + \ldots + RC^{ds_i} \\ & \cdot \Pr(DS = ds_i); \; i = 1 \ldots n \end{aligned} \qquad (10.2)$$

In essence, the integral expression in Eq. (10.1) computes the expected annual loss of an asset by considering a range of GMIM, s, that are likely to occur at the site with different annual probabilities. If the consequence model used in Eq. (10.2) is dimensionless (in terms of replacement cost ratio), the resulting loss by Eq. (10.1) is called as average annual loss ratio (AALR); favored more by the insurance industry.

The accuracy of the predicted loss (in this case AAL or AALR) is confined to the reliable seismic hazard and vulnerability models hence the consistent fragility and consequence functions. This fact brings forward the modeling uncertainty (epistemic uncertainty) in these components that is addressed in a variety of scientific publications. A fairly ample review, in this respect, can be found in FEMA P-58

(ATC 2018). The lack of knowledge, insufficient data and subsequent assumptions as well as interpretations about the model behavior are the main sources of epistemic uncertainty.

This article presents a case study on modeling the uncertainty in content vulnerability functions for residential buildings in Turkey and its progressive influence on the loss computations. Since vulnerability functions are composed of fragility and consequence models (Eq. (10.2)), the progressive influence of the epistemic uncertainty is discussed by considering the interaction between these two modeling elements. The contents considered here are poorly anchored or unanchored house utensils as well as furniture and electronic equipment frequently used in the residential dwellings. Their fragility modeling presented here is conditioned on the different levels of building damage that would lead to more accountable loss predictions.

The paper starts by describing the development of content fragilities conditioned on the building damage that is followed by the development of consequence functions for different modes of content damage. The associated epistemic uncertainty in the conditional content fragilities and consequence functions are progressed to observe their influence on the content vulnerability model. To illustrate the implementation of the discussions, the last part in the paper integrates the conditional vulnerability model together with the most recent national seismic hazard maps to compute the distribution of residential building content AALR for entire Turkey.

10.2 Development of Content Fragilities Conditioned on Building Damage

10.2.1 Review of Some Benchmark Documents

ATC-13 (1985), the HAZUS technical report (FEMA 2003) and FEMA P-58 (ATC 2018) are comprehensive documents proposing methodologies to predict content damage loss for different structural facilities due to ground shaking. ATC-13 (1985), which can be considered as one of the pioneer guidelines in earthquake loss assessment provides content (equipment) fragilities as functions of Modified Mercalli Intenisty (MMI) GMIM. The fragilities are developed by the expert opinions of a group of earthquake engineering specialists. The expert-based content fragilities by ATC-13 (1985) rely on the assumptions of

(a)   regular building construction quality,
(b)   structures on firm soil,
(c)   merely ground shaking without damage aggravation due to collateral hazard (e.g., fire, fault rupture and inundation) and,
(d)   the content is at the ground level and unanchored.

Assuming that the content damage is floor acceleration sensitive, the HAZUS technical report (FEMA 2003) provides an empirical formulation for content loss that depends on

(a)   structural damage states,
(b)   building-type sensitive content replacement value and,
(c)   the probability of building being in non-structural acceleration sensitive damage state.

FEMA P-58 (ATC 2018) apriori assumes that the contents are sensitive to peak floor acceleration and velocity, and provides building-type dependent content fragilities as well as normative content quantitates to predict the content loss under ground shaking. The content loss assessment tools provided in the FEMA P-58 and HAZUS documents are more comprehensive than the one in ATC-13 but it seems that they are more suitable to assess a specific single asset as long as the content loss is of concern. Naturally, all three documents establish their methodologies considering the structural typologies and construction quality in the United States. In fact, ATC-13 (1985) was prepared for earthquake loss in California.

10.2.2   Theoretical Background

The content fragilities developed in this section are also conditioned on the building damage as in the case of the HAZUS technical report but their underlying theory utilizes total probability theorem as partially illustrated in Fig. 10.1. In other words, the content damage probability is decomposed into different states $(ds_1^{cnt}, \ldots, ds_5^{cnt})$ that are jointly distributed with different building damage states. As presented in
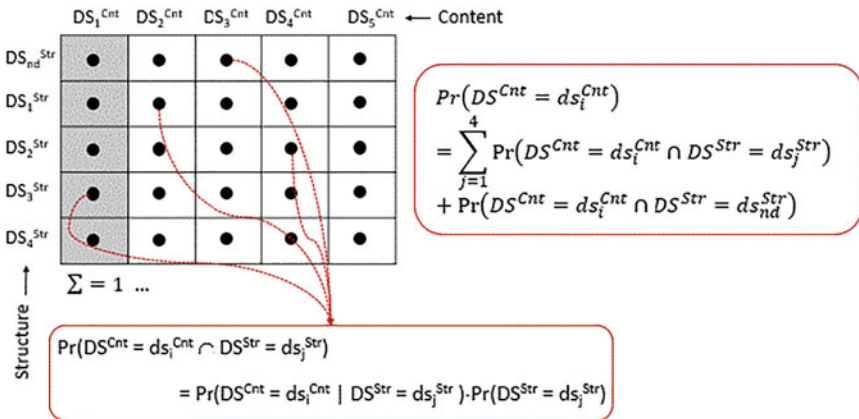

Fig. 10.1 Schematic diagram showing the dependency (interaction) of content and structural damage and its representation in probabilistic terms

Fig. 10.1, the probability that the content is at the damage state $DS^{Cnt} = ds_i^{cnt}$ is the sum of the joint probabilities of the content damage $DS^{Cnt} = ds_i^{cnt}$ and all building damage states, $DS^{Str} = ds_j^{str}$, $j = 1,…,n_{str}$, as well as the likelihood of building being not damaged, $DS^{Str} = ds_{nd}^{str}$.

Equation (10.3) defines the same content damage probability in terms of conditional probabilities where $Pr\left(DS^{Cnt} = ds_i^{Cnt}|DS^{Str} = ds_j^{Str}\right)$ is the ith state content damage probability conditioned on the jth state building damage and $Pr\left(DS^{Cnt} = ds_i^{Cnt}|DS^{Str} = ds_{nd}^{Str}\right)$ is the ith state content damage probability conditioned on undamaged building state. The terms $Pr\left(DS^{Str} = ds_j^{Str}\right)$ and $Pr\left(DS^{Str} = ds_{nd}^{Str}\right)$ refer to the jth damage state and no damage state probabilities of the building, respectively.

$$\Pr(DS^{Cnt} = ds_i^{Cnt}) = \sum_{j=1}^{4} \Pr(DS^{Cnt} = ds_i^{Cnt} \mid DS^{Str} = ds_j^{Str}) \cdot \Pr(DS^{Str} = ds_j^{Str})$$
$$+ \Pr(DS^{Cnt} = ds_i^{Cnt} \mid DS^{Str} = ds_{nd}^{Str}) \tag{10.3}$$

The difficulty in the implementation of Eq. (10.3) is the unknown conditional probabilities (i.e., $Pr\left(DS^{Cnt} = ds_i^{Cnt}|DS^{Str} = ds_j^{Str}\right)$). The other probabilities, that is, the probabilities of building being in a damage state ds_j^{Str} or being in no damage state $DS^{Str} = ds_{nd}^{Str}$ can be determined from the building fragilities. The way to surmount the unknown conditional probabilities can be the utilization of Monte Carlo sampling technique as explained in the next paragraph but before that Fig. 10.2 shows the discrete building and content damage states that are used in their fragility functions and the corresponding descriptions of the content damage states for clarity.

Figure 10.3 displays the concept in proposed approach while generating the content damage probabilities conditioned on the building damage. When the building does not suffer any structural damage, the content is most likely to be slightly damaged for not being properly anchored on the floor. Consequently, the building suffering from light, moderate to severe and very severe (collapse or almost collapse)

Building

- $DS_1{}^{Str}$: **Light** structural damage
- $DS_2{}^{Str}$: **Moderate** structural damage
- $DS_3{}^{Str}$: **Severe** structural damage
- $DS_4{}^{Str}$: **Very severe** (almost collapse) structural damage

Content

- $DS_1{}^{Cnt}$: **Slight** (limited localized) content damage not requiring repair
- $DS_2{}^{Cnt}$: **Light** (significant localized) content damage generally not requiring repair
- $DS_3{}^{Cnt}$: **Moderate** (significant localized) content damage warranting repair
- $DS_4{}^{Cnt}$: **Heavy** (extensive) content damage requiring major repairs
- $DS_5{}^{Cnt}$: **Very heavy** (widespread) content damage either demolished or repaired

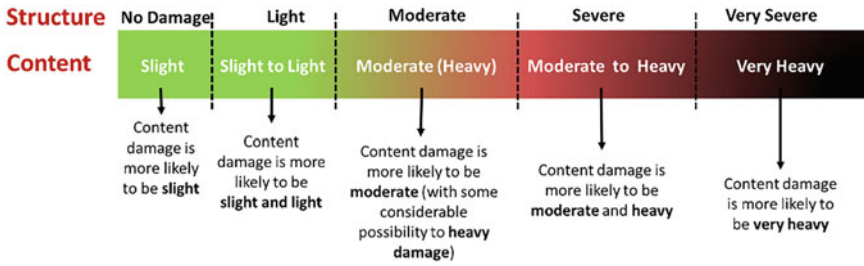**Fig. 10.2** Descriptions of building and content damage states

Fig. 10.3 The concept used while generating the content damage probabilities conditioned on building damage

damage states result in slight to very heavy content damages associated with different probabilities. The implementation of this conceptual approach to sample conditional content damage probabilities are illustrated for three different cases in Figs. 10.4, 10.5 and 10.6 representing, respectively, no structural damage, moderate structural damage and very heavy structural damage states of a residential building.

Figure 10.4 indicates that the content damage probabilities are assumed to be represented by three different damage states (slight, light and moderate) when the building sheltering the content does not suffer any structural damage (i.e., when only a limited nonstructural damage is observed in the architectural and mechanical/electrical building components). Note that the approach primarily rates the slight content damage, which is followed by the light and moderate damages associated
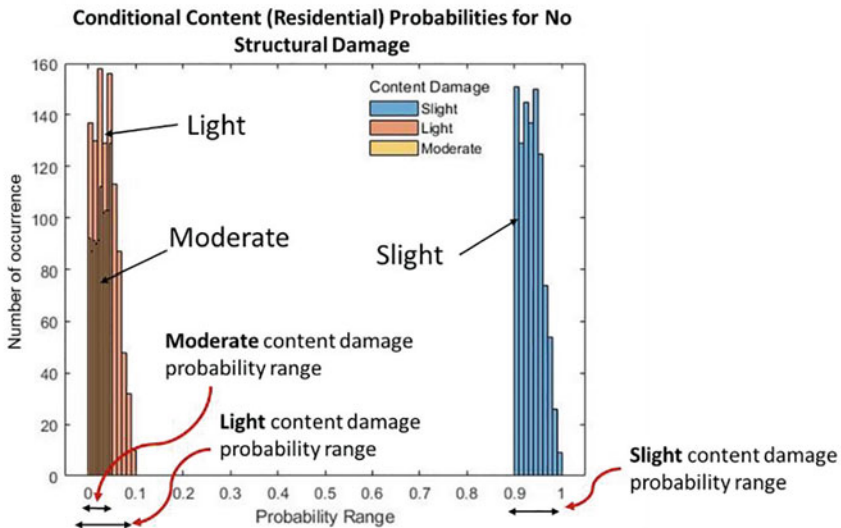
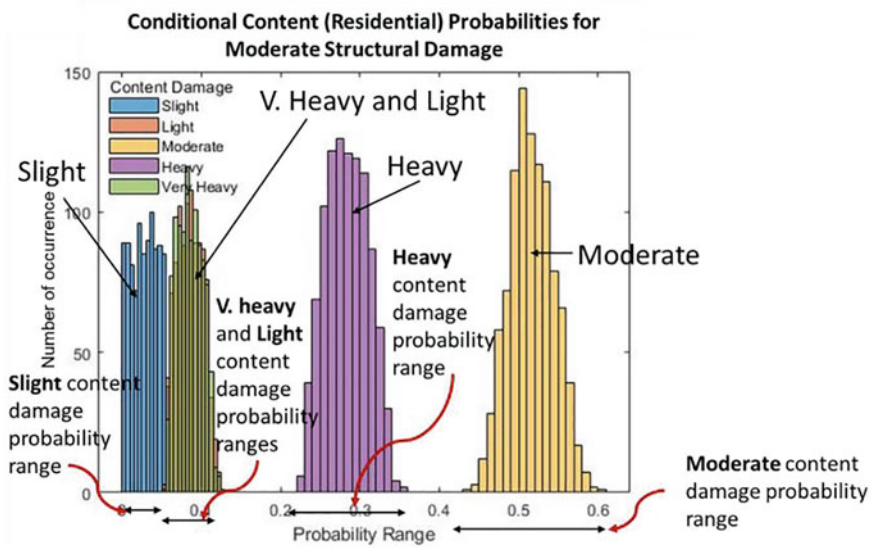**Fig. 10.4** Distribution of content damage probabilities conditioned on no structure damage in the building

Fig. 10.5 Distribution of content damage probabilities conditioned on moderate structural damage in the building
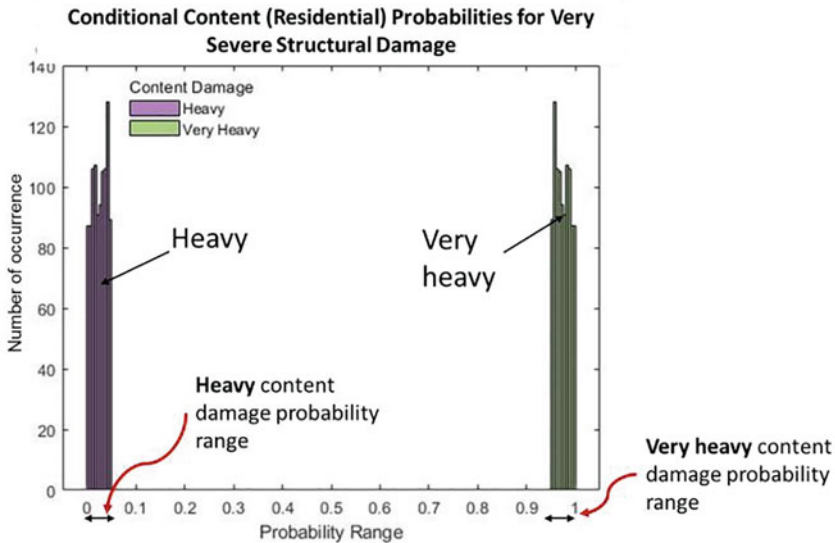

Fig. 10.6 Distribution of content damage probabilities conditioned on very severe structural damage in the building

with very small probabilities. When the building suffers from moderate structural damage (Fig. 10.5), the content damage probabilities are represented by all five states and the proposed approach apriori prefers moderate content damage and then rates the occurrence probability of heavy content damage more than the other three damage states (slight, light and very heavy). Note that the likelihood of very heavy content damage is more than the slight content damage prorating the existence of fragile content in the residential buildings. Upon very severe structural damage (Fig. 10.6), the approach almost exclusively favors very have content damage, practically advocating its full replacement. As a final remark, the sampling should be tailored such that given building damage state, the assigned content damage probabilities should sum up to unity at every sampling.

10.2.3 Case Studies on Developed Content Fragilities

Figures 10.7 and 10.8 show a case on the implementation of the proposed approach. The case study develops content fragilities for a mid-rise reinforced concrete (RC) moment-resisting frame (MRF) residential building, representative of its class, in Turkey. The building damage state probabilities presented in Fig. 10.7 are generated from the fragility study conducted for the Turkish Catastrophe Insurance Pool (TCIP) to revise the compulsory earthquake premiums of residential buildings in Turkey (TDV 2018). The fragility study compiled the reliable fragility models that are representatives of residential buildings in Turkey to develop homogenized fragility models in terms of construction date (No-code -pre1976-, Low-code -1976 to 2000- and High-code -post2000) and story number (Low-rise $-\leq$ 3-story, Mid-rise -4 to 9

Fig. 10.7 Populated damage probabilities at different states for mid-rise (4 to 9 story) reinforced concrete residential building class in Turkey built after 2000 (considered as high-code)
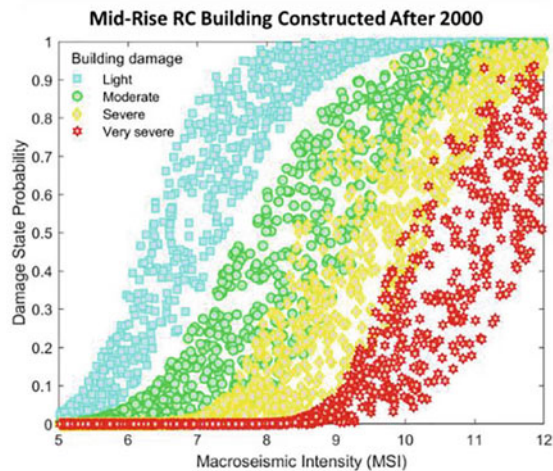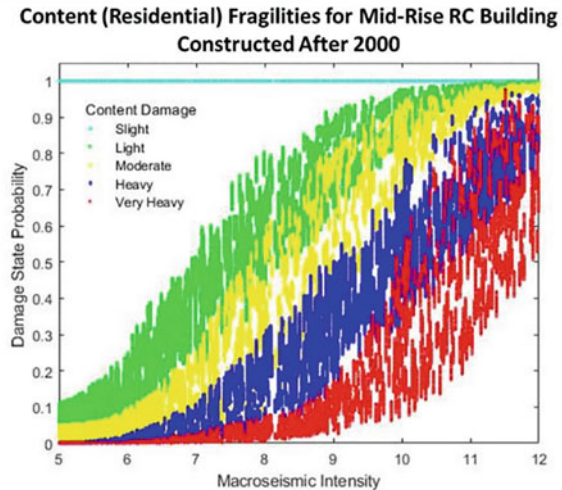
Fig. 10.8 Content damage probabilities at different states for mid-rise, high-code residential building class (see Fig. 10.7) in Turkey

story, and High-rise –9 to 19 story). The fragilities are developed as functions of modified Mercalli Intensity (MMI) scale because some of the fragility models compiled during the fragility study were developed from on-site damage observations after the earthquakes.

The sampled building damage probabilities presented in Fig. 10.7 account for the variability at each damage state due to:

a.   uncertainty in the damage state threshold by different studies,
b.   variability in the modeling aspects of the buildings and,
c.   variability in building response due to intricate nature of earthquake ground-motion records.

For this reason, the Monte Carlo sampling results in bands of probabilities given a specific MMI value. The upper and lower end of the bands, hence the damage probabilities, overlap each other due to excessive variability in the fragilities at each damage state.

Figure 10.8 shows the content fragilities for the same residential building class after implementing Eq. (10.3). The conditional content probabilities conditioned on different building damage states and the building damage probabilities are populated as described in the above paragraphs. They are presented in Figs. 10.4, 10.5, 10.6 and 10.7. To this end, the resulting content fragilities account for the model uncertainty due to building response and content damageability associated with differences in the residential equipment, their locations, placements and etc. That's why the overlapping of damage probabilities at different content damage states are increased with respect to those presented for the buildings (Fig. 10.7).

Figure 10.9 shows the same content fragilities for no-code, mid-rise MRF residential buildings. Hence, the building damage probabilities are revised in these calculations to account for no-code mid-rise building performance under seismic action.

Fig. 10.9 Content damage
probabilities at different
states for mid-rise, no-code
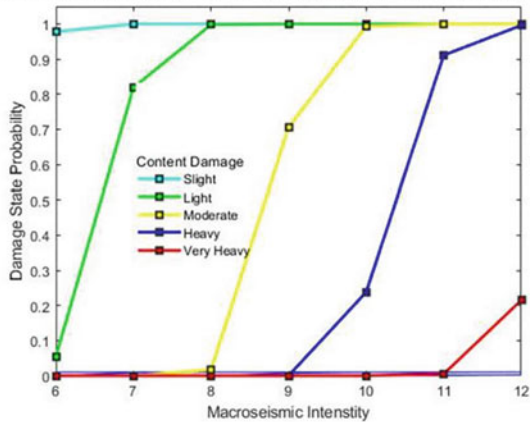residential building (see
Fig. 10.7) in Turkey
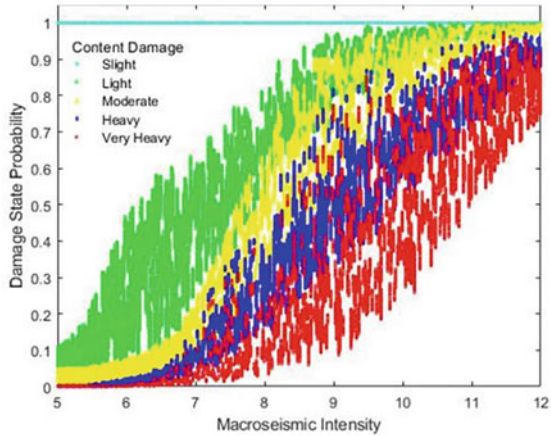
The conditional content damage probabilities are also repopulated by considering
the change in the building typology. The comparisons between Figs. 10.8 and 10.9
underline the significance of building performance in the content fragility. Conse-
quently, the contents in low-code and old residential buildings are more susceptible
to damage with respect to those in new and high-code buildings.

As for the last discussion in this section, Fig. 10.10 shows the content damage
fragilities provided by ATC-13 (1985) for California under the assumptions presented
in the beginning of this section. The damage state definitions in this study and
the ATC-13 document is the same. ATC-13 provides damage probability matrices

Fig. 10.10 Content damage
fragilities provide in ATC-13
(1985) for residential RC
buildings in California

(DPMs) for each target facility class (one of them is the content for residential build-ings) after the evaluation of three-round questionnaires. The DPMs for the residential content are converted to fragilities as presented in Fig. 10.10.

The comparisons of content fragilities provided in this study and those given in the ATC-13 document are in agreement to a limited extent. There are major differences in terms of the uncertainty in content damageability predictions by each approach. ATC-13 defines a unique content damage probability at each damage state given a specific MMI value. The content fragilities developed in this study yield a range of damage probability at each content damage state by considering the progression of the epistemic uncertainty in building response as well as content damageability. As depicted by Figs. 10.9 and 10.10, the slight content damage is similarly predicted by the two studies but the ATC-13 probabilities for the rest of the damage states seem to be closer to the lower bound fragility predictions of this study. Hence, upon the use of these two different fragility sets in a probabilistic risk assessment study, one may obtain completely different loss pictures. This fact brings forward the importance of how epistemic uncertainties are handled in a given methodology as well as the country-based differences in loss assessment.

10.3   Content Consequence Model

The replacement cost ratios for content is modeled from expert opinions of risk engineers working in the field of insurance. The experts filled a questionnaire about the replacement cost ratios of a variety of residential equipment (content) subjected to various levels of damage (slight to very heavy as defined in Fig. 10.2). The expert opinions were pooled under a database and several group meetings were held with the experts to reach a common agreement for removing the outlier judgements. The improved expert opinion database was then used to compute the means and the standard deviations of the replacement cost ratios for the predetermined damage states. Given a damage state, the dispersion about its mean replacement cost ratio was used to establish an interval defining the lower and upper boundaries of the replacement cost ratio. This interval accounts for the epistemic uncertainty in the insurance-based replacement cost of the subject content for that specific damage state due to differences in the expert considerations. Figure 10.11 depicts the resulting content model for all five states of the content damage.

The Monte Carlo simulations were utilized to randomly sample the model uncer-tainty in the content replacement cost ratios. Figure 10.12 displays the randomly sampled replacement cost ratio distributions at each damage state. The replacement cost ratio sampling assumed uniform distribution for this case study though it could also have been any other distribution mimicking a more realistic representation of the replacement cost ratio. The sampled replacement cost ratios and the populated content damage probabilities presented in the previous sections were used in Eq. (10.2) to develop the content vulnerability model that is discussed further in the following section.

Fig. 10.11 Content
consequence model
(replacement cost ratio) used
in this study. The likely
replacement cost ratios given
a specific content damage
state are described within the
horizontal gray bars. D1:
slight, D2: light, D3:
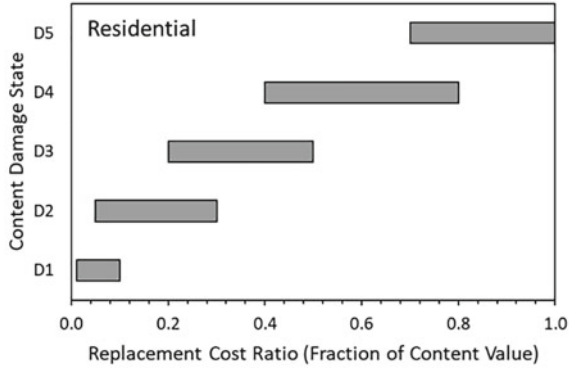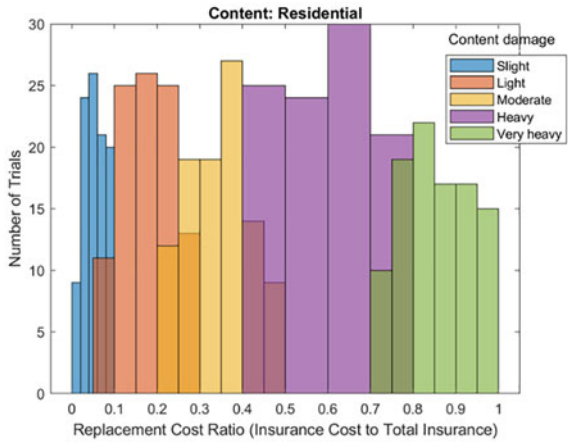moderate, D4: heavy, D5:
very heavy content damages

Fig. 10.12 Replacement
cost ratio distributions
generated from Monte Carlo
simulations for each content
damage state

10.4 Vulnerability Model and Country-Wide Content AALR

The sampled content damage probabilities as well as the replacement cost ratios as discussed in the last two sections were input into Eq. (10.2) to develop the compound loses for residential content. As an example, Fig. 10.13 gives the resulting content loss model for high-code, mid-rise RC MRF buildings in Turkey. The gray cloud in this figure illustrates all possible combinations of the sampled content damage probabilities and the replacement cost ratios. The content losses computed from the combinations of damage probabilities and replacement cost ratios depict a very large range, which indicates the progression of epistemic uncertainty from building damage probabilities to content loss conditioned on the building damage as well as the monetary consequences of content damaged at different levels. The median loss (red curve) represents the central trend in the content loss whereas the blue scatters represent the body of the content loss predictions. In other words, the median loss

Fig. 10.13 Content loss (vulnerability) dispersion for mid-rise and high-code RC buildings after combining the content damage probabilities and the consequential replacement cost ratios discussed in the previous sections

Content (Residential) Loss for Mid-Rise RC Building Constructed After 2000
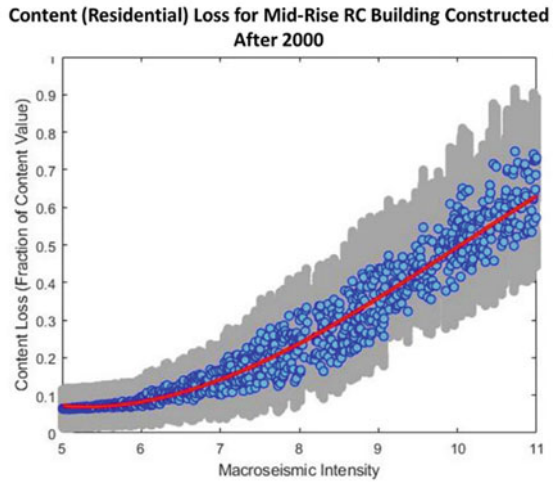
can be interpreted as the most expected (best estimate) content loss trend, whereas the boundaries represented by the body (blue scatters) yield the higher and lower loss values of alternative interpretations in the content damage probabilities as well as the replacement costs. The upper and lower limits of the range (gray cloud) can be interpreted as the extreme content losses that are beyond the empirical data but still have justifiable bases if they are to incur. Note that the increased ground-motion intensity results in higher dispersion in the content loss. This fact advocates a more dominant epistemic uncertainty in the main components of the content vulnerability with increasing ground-motion amplitude.

The last figure in this paper (Fig. 10.14) presents the AALR distribution for residential content in the mid-rise, high-code MRF buildings in Turkey. The median content vulnerability curve as presented in Fig. 10.13 and the soil-condition sensitive

Fig. 10.14 AALR distribution for mainland Turkey for residential content in high-code, mid-rise RC MRFs
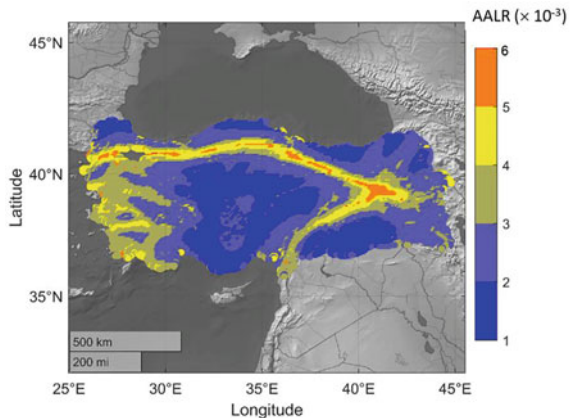
hazard curves developed from the most recent national seismic hazard map (Akkar et al. 2018) were used in Eq. (10.1) for calculations. The site conditions for the entire country were adopted from the overall countrywide geology whereas the PGA and PGV values at different annual exceedance rates by the national seismic hazard maps were converted to MMI via Wald et al. (1999) for estimating the MMI-based hazard. The details of these calculations are discussed in the TDV report (TDV 2018).

The maps suggest an AALR interval ranging between 4×10^{-3} and 6×10^{-3} for the most seismic prone settlements in Turkey (e.g., Istanbul, Izmir, Canakkale, Erzincan, Aydin, Denizli, etc.). This value suggests a yearly basis pure premium of €40 to €60 Euros for residential equipment of €10,000 worth in such cities. The AALR values go down to as much as 1×10^{-3} (i.e., a yearly basis pure premium of €10 for residential equipment of €10,000 worth) in the least seismic regions in the country such as the large portion of the south Eastern Turkey and the central Anatolia. Needless to say the presented numbers are valid for the residential content in the mid-rise, high-code, MRF buildings. They would be scaled up and down depending on the building type, construction period and height as partially discussed in Fig. 10.9.

10.5 Summary and Conclusions

This study proposes a procedure to develop content fragilities conditioned on building damage for loss and risk modeling that can be used in computing metrics relevant to insurance and reinsurance. The conditional content fragilities can account for the epistemic uncertainty in assessing the earthquake induced building damage states as well as the different likelihoods of content damage under different modalities of building damage. These uncertainties are handled via Monte Carlo sampling that enables the risk expert to trace forward or backward the progression of model uncertainty and its effects on the computed loss and risk. The proposed procedure is analytical, and its systematic utilization can result in country-specific vulnerability and risk models. This feature makes the procedure appealing because the current well-organized and state-of-the-art tools in this field seem to be tailored for the construction quality and building classification in the US practice (e.g., ATC-13 1985; FEMA 2003). The systematic efforts for improving this procedure should involve calibrations through comparisons with other approaches as well as sensitivity analyses to understand the behavior of critical components contributing the most to loss and risk assessment results.

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