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Calculation of Buildings Damage Estimation and Retrofit cost

Industrial and Systems Engineering
Gallogly College of Engineering
University of Oklahoma

Building functionality

Building restoration function

(Koliou and van de Lindt, 2019)

$$Q_{ijk}^{t} = \frac{\frac{Q_{ijk}^{0}}{e^{-r_{ijk}t}}}{\frac{Q_{ijk}^{0}}{e^{-r_{ijk}t}} + (1 - Q_{ijk}^{0})}$$

Q_{ijk}^{t} : $Building\ functionality$

Q_{ijk}^{0} : $Starting\ level\ of\ building\ functionality\ right\ after\ disaster$

r_{ijk} : $based\ on\ Q_{ijk}^{0}\ and\ repair\ time\ to\ reach\ 100\%\ of\ building\ functionality$

t: $recovery\ time\ after\ disaster\ impact$

Damage State and Damage Factor

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Table 2. ATC-13 Damage States and Corresponding Damage Factor Ranges [Adapted from Applied Technology Council (ATC 1985)]

Damage state	Damage factor range (%)
1–None	0
2–Slight	0–1
3–Light	1–10
4–Moderate	10–30
5–Heavy	30–60
6–Major	60–100
7–Destroyed	100

(Bai et al,2009)

There is no study done about the damage states and damage factor for tornado disaster. Therefore, I used the available information from earthquake studies to proposed a table for Joplin project.

Damage State and Damage Factor for Joplin

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There is no study done about the damage states and damage factor for tornado disaster. Therefore, we proposed the following table for Joplin project to calculated the loss estimation and initial values of buildings functionality.

Damage State	Damage Factor(%)
None(N)	0
Insignificant(I)	5
Moderate(M)	30
Heavy(H)	68
Complete(C)	100

Tornado Building Fragility Curve Parameters

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We use this information to create fragility curve on building type 1 and 5

Considered Retrofit Strategies Based on Different Types of Roof Covering, Roof Sheathing Nailing Patterns, and Roof-to-Wall Connections

Retrofit strategies #	Roof covering		Roof sheathing nailing pattern		Roof-to-wall connection type		
	Asphalt shingles	Clay tiles	8d C6/12	8d C6/6	Two 16d toe nails	H2.5 clip	Two H2.5 clips
1	X	-	X	-	X	-	-
2	X	-	-	X	-	-	X
3	-	X	-	X	-	-	X

Note: this table is referenced from the paper written by Masoomi et al. (2017)

Building-level Tornado Fragility Curves for Residential Buildings (Archetype 1 - Archetype 5)

Damage state	Construction product combination #	Archetype 1		Archetype 2		Archetype 3		Archetype 4		Archetype 5	
		μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
DS1	1	3.47 (4.28)	0.14 (0.14)	3.44 (4.25)	0.14 (0.13)	3.43 (4.24)	0.14 (0.14)	3.57 (4.37)	0.13 (0.13)	3.41 (4.21)	0.13 (0.13)
	2	3.86 (4.67)	0.14 (0.14)	3.82 (4.62)	0.14 (0.14)	3.82 (4.63)	0.14 (0.14)	3.83 (4.64)	0.14 (0.14)	3.79 (4.59)	0.14 (0.14)
	3	3.87 (4.68)	0.15 (0.15)	3.84 (4.64)	0.14 (0.14)	3.83 (4.64)	0.14 (0.14)	3.96 (4.77)	0.14 (0.14)	3.80 (4.60)	0.14 (0.14)
DS2	1	3.55 (4.35)	0.13 (0.13)	3.51 (4.32)	0.12 (0.12)	3.50 (4.31)	0.12 (0.12)	3.63 (4.44)	0.12 (0.12)	3.47 (4.28)	0.12 (0.12)
	2	3.93 (4.74)	0.13 (0.13)	3.88 (4.68)	0.13 (0.13)	3.89 (4.70)	0.13 (0.13)	3.89 (4.70)	0.12 (0.12)	3.86 (4.66)	0.12 (0.12)
	3	3.95 (4.76)	0.13 (0.13)	3.91 (4.72)	0.12 (0.12)	3.91 (4.71)	0.13 (0.13)	4.04 (4.84)	0.12 (0.12)	3.87 (4.68)	0.12 (0.12)
DS3	1	3.62 (4.42)	0.12 (0.12)	3.57 (4.38)	0.12 (0.12)	3.57 (4.38)	0.12 (0.12)	3.70 (4.50)	0.12 (0.12)	3.53 (4.34)	0.12 (0.12)
	2	4.01 (4.82)	0.12 (0.12)	3.95 (4.75)	0.11 (0.12)	3.97 (4.78)	0.11 (0.11)	4.04 (4.85)	0.11 (0.11)	3.94 (4.74)	0.12 (0.12)
	3	4.03 (4.84)	0.12 (0.12)	3.98 (4.79)	0.12 (0.12)	3.98 (4.79)	0.12 (0.12)	4.10 (4.90)	0.12 (0.12)	3.94 (4.75)	0.12 (0.12)
DS4	1	3.64 (4.45)	0.14 (0.15)	3.57 (4.37)	0.15 (0.14)	3.61 (4.42)	0.14 (0.15)	3.61 (4.41)	0.14 (0.15)	3.50 (4.31)	0.15 (0.15)
	2	4.05 (4.86)	0.12 (0.12)	3.97 (4.77)	0.12 (0.12)	4.03 (4.83)	0.12 (0.12)	4.04 (4.84)	0.11 (0.11)	3.98 (4.78)	0.11 (0.11)
	3	4.24 (5.04)	0.12 (0.12)	4.14 (4.94)	0.12 (0.12)	4.21 (5.02)	0.12 (0.12)	4.18 (4.98)	0.13 (0.13)	4.03 (4.84)	0.14 (0.14)

Note: μ refers to logarithimic mean of curves and σ refers to logarithmic standard deviation of curves, and the unit is m/s (mph).

(Masoomi et al ,2018)

Actual data of Fragility curve for Joplin

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		DS1			DS2			DS3			DS4		
	Wind Speed	Strategy1	Strategy2	Strategy3	Strategy1	Strategy2	Strategy3	Strategy1	Strategy2	Strategy3	Strategy1	Strategy2	Strategy3
		3.47	3.86	3.87	3.55	3.93	3.95	3.62	4.01	4.03	3.64	4.05	4.24
		0.14	0.14	0.15	0.13	0.13	0.13	0.12	0.12	0.12	0.14	0.12	0.12
	20	0.0003525	3.34309E-10	2.7972E-09	1.0058E-05	3.31941E-13	1.06382E-13	9.84551E-08	1.4289E-17	3.3801E-18	2.09315E-06	7.7791E-19	1.71732E-25
	24	0.01851969	5.5505E-07	1.9847E-06	0.00211071	3.64288E-09	1.44218E-09	0.000115305	2.0617E-12	6.2581E-13	0.000484087	1.8485E-13	4.39359E-19
	28	0.16249544	8.16343E-05	0.00016834	0.0469328	2.12847E-06	1.00571E-06	0.00823578	8.1023E-09	3.0324E-09	0.013955352	1.1046E-09	1.93988E-14
	32	0.48785096	0.002429981	0.00351844	0.25843253	0.000177632	9.76156E-05	0.099302847	2.8729E-06	1.2869E-06	0.106613016	5.612E-07	5.51187E-11
	36	0.79127397	0.024141751	0.02807474	0.60173403	0.003846682	0.002408037	0.380560576	0.0001897	9.9345E-05	0.343313697	5.0674E-05	2.24162E-08
	40	0.94102363	0.110799063	0.11362554	0.85730818	0.031814294	0.022288746	0.71701456	0.00372528	0.00223686	0.636507505	0.00130909	2.18804E-06
	44	0.98759061	0.294080598	0.28363758	0.9641847	0.131012405	0.101072467	0.914382605	0.02993478	0.02025945	0.848477618	0.01337707	7.28108E-05
	48	0.9979197	0.531884243	0.50319419	0.99325901	0.325526468	0.27220888	0.981840671	0.12370601	0.09286368	0.950675189	0.06811323	0.001058439
Archtype 1	52	0.9997064	0.742715816	0.70596149	0.99898733	0.564903453	0.503816649	0.997113153	0.31219586	0.2558148	0.986897811	0.20526281	0.008057461
	56	0.99996358	0.881215224	0.84982379	0.99987218	0.768365476	0.718917378	0.999634833	0.55089811	0.48455047	0.997043002	0.4186288	0.036828678
	60	0.99999589	0.952923864	0.932625	0.99998588	0.89691889	0.866574329	0.999961391	0.75893204	0.70409145	0.999413403	0.64413663	0.112412948
	64	0.99999957	0.983614559	0.97294077	0.99999859	0.960850247	0.945950102	0.99999645	0.89264029	0.85859442	0.999894849	0.81789152	0.249528479
	68	0.99999996	0.994884346	0.99009828	0.99999987	0.987025773	0.980920197	0.999999707	0.95958562	0.94285844	0.999982585	0.92110805	0.432202654
	72	1	0.998540714	0.99664706	0.99999999	0.996169571	0.994011416	0.999999978	0.9868657	0.98008709	0.999997287	0.97054633	0.62002673
	76	1	0.999613633	0.99893527	1	0.998973873	0.998298185	0.999999998	0.9962387	0.99389664	0.999999597	0.99034378	0.775208727
	80	1	0.999903788	0.99967934	1	0.999746592	0.999555175	1	0.99903312	0.99832448	0.999999942	0.9971703	0.881705426
	84	1	0.999977216	0.99990754	1	0.999941526	0.9998916	1	0.99977324	0.99958132	0.999999992	0.99924687	0.944098373
	88	1	0.999994821	0.99997427	1	0.999987247	0.999975087	1	0.99995079	0.99990342	0.999999999	0.99981538	0.976024746
	92	1	0.999998861	0.99999304	1	0.999997346	0.999994547	1	0.99999	0.99997918	1	0.9999578	0.990568771
	96	1	0.999999756	0.99999816	1	0.999999468	0.999998854	1	0.99999808	0.99999576	1	0.99999091	0.996563145
	100	1	0.999999949	0.99999952	1	0.999999897	0.999999767	1	0.99999965	0.99999918	1	0.99999814	0.998829169
		DS1			DS2			DS3			DS4		
	Wind Speed	Strategy1	Strategy2	Strategy3	Strategy1	Strategy2	Strategy3	Strategy1	Strategy2	Strategy3	Strategy1	Strategy2	Strategy3
		3.41	3.79	3.8	3.47	3.86	3.87	3.53	3.94	3.94	3.5	3.98	4.03
		0.13	0.14	0.14	0.12	0.12	0.12	0.12	0.12	0.12	0.15	0.11	0.14
	20	0.00071959	7.00196E-09	4.6023E-09	3.8713E-05	2.96176E-13	1.60163E-13	4.24913E-06	1.7889E-15	1.7889E-15	0.000387202	1.8117E-19	7.47364E-14
	24	0.03719548	6.18269E-06	4.4465E-06	0.00748953	6.62208E-09	4.05351E-09	0.001679143	1.0797E-10	1.0797E-10	0.015924215	1.545E-13	5.81259E-10
	28	0.27477758	0.000537799	0.00041679	0.12542325	5.45521E-06	3.70377E-06	0.049645998	2.0424E-07	2.0424E-07	0.131647602	1.9421E-09	3.11007E-07
	32	0.66594294	0.010274436	0.00847938	0.48582691	0.000508946	0.000377389	0.296140277	3.8718E-05	3.8718E-05	0.409657028	1.4689E-06	2.78342E-05
	36	0.90902272	0.070124458	0.06101688	0.82792345	0.010611074	0.008485344	0.672198182	0.00148573	0.00148573	0.71116554	0.00015645	0.000713458
	40	0.98403263	0.235058219	0.21367976	0.96592362	0.076933514	0.065606229	0.907247722	0.01818926	0.01818926	0.896020292	0.00406587	0.00741354
	44	0.99800139	0.483447604	0.45504256	0.99558086	0.263774128	0.237277833	0.982922921	0.09707157	0.09707157	0.970927131	0.03753027	0.039562279
	48	0.99980569	0.719045126	0.6944762	0.99958612	0.53718397	0.503992717	0.997767841	0.28321236	0.28321236	0.993332097	0.16131158	0.128338874
Archtype 5	52	0.99998432	0.875286209	0.85999843	0.99996969	0.776481578	0.750806853	0.999776253	0.53732533	0.53732533	0.998686395	0.39688403	0.286872422
	56	0.9999989	0.953626652	0.9462634	0.99999815	0.915887666	0.902270429	0.999981698	0.7615397	0.7615397	0.999769409	0.65993586	0.486756668
	60	0.99999993	0.985143291	0.98224355	0.9999999	0.974582579	0.969226	0.999998717	0.90081418	0.90081418	0.999962884	0.85071295	0.677099762
	64	1	0.995791638	0.99481813	1	0.993625277	0.991965818	0.99999992	0.96592591	0.96592591	0.999994399	0.94804749	0.821368639
	68	1	0.9989222	0.99863444	1	0.998631808	0.998207628	0.999999995	0.99007658	0.99007658	0.999999194	0.9852725	0.91207221
	72	1	0.999745701	0.99966889	1	0.999741911	0.999649112	1	0.99748847	0.99748847	0.999999888	0.99650127	0.960956975
	76	1	0.999943856	0.99992496	1	0.999956233	0.999938344	1	0.99943525	0.99943525	0.999999985	0.9992849	0.984146907
	80	1	0.999988251	0.9999839	1	0.9999932	0.999990089	1	0.999885	0.999885	0.999999998	0.9998713	0.994039529
	84	1	0.999997645	0.99999669	1	0.999999017	0.999998519	1	0.99997844	0.99997844	1	0.99997919	0.997901596
	88	1	0.999999544	0.99999934	1	0.999999866	0.999999792	1	0.99999623	0.99999623	1	0.99999693	0.999301483
	92	1	0.999999914	0.99999987	1	0.999999983	0.999999972	1	0.99999938	0.99999938	1	0.99999958	0.999778274
	96	1	0.999999984	0.99999998	1	0.999999998	0.999999996	1	0.9999999	0.9999999	1	0.99999995	0.999932396
	100	1	0.999999997	1	1	1	1	1	0.99999999	0.99999999	1	0.99999999	0.999980076

Tornado Building Fragility Curve

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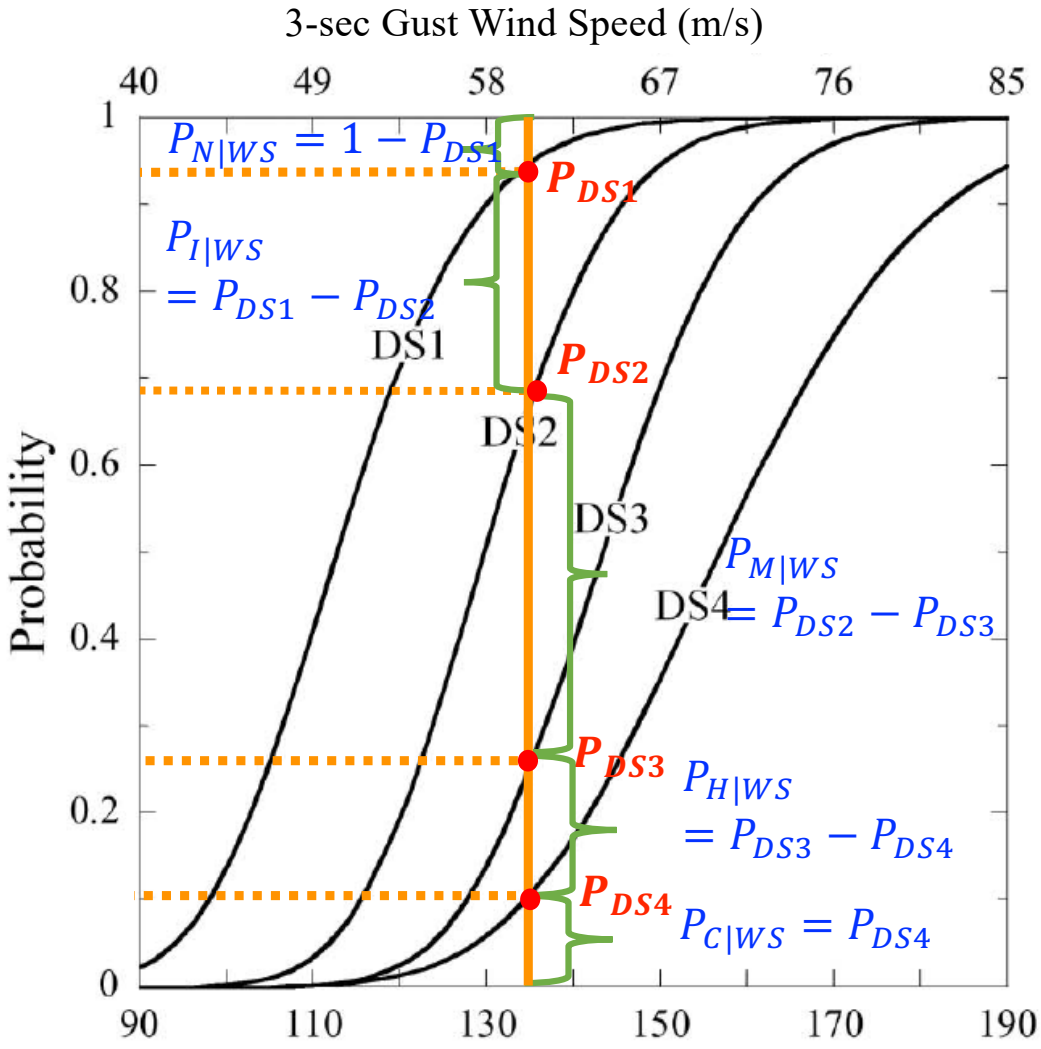
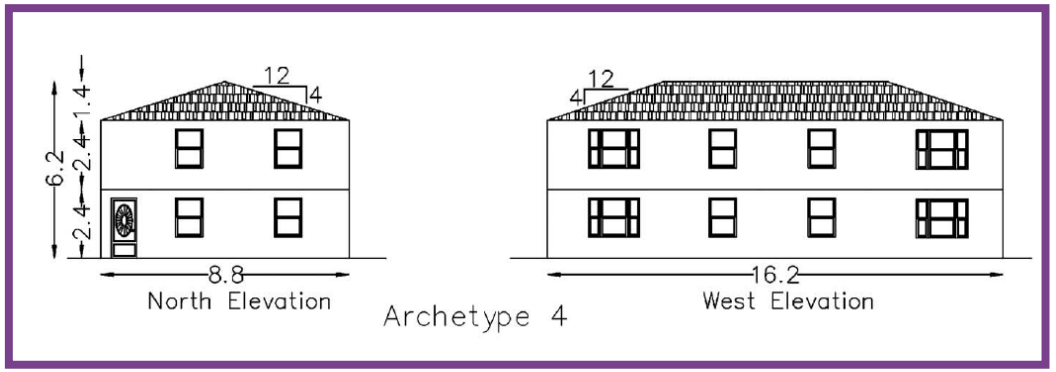


(Source: Masoomi et al,2018)

Table 1. Damage States for the Wood-Frame Building

Damage state	Damage indicators			
	Roof covering failure	Window/door failure	Roof sheathing failure	Roof-to-wall connection failure
1	>2% and ≤15%[a]	1[a]	No	No
2	>15% and ≤50%[a]	2 or 3[a]	1–3[a]	No
3	>50%[a]	>3[a]	>3 and ≤35%[a]	No
4	Typically > 50%	Typically > 3	>35%[a]	Yes[a]

Note: Each damage state is defined as occurrence of any of the damage indicators in a given row marked with [a].



Structure associated with the fragility curve
Wood frame residential building (Multi-family building)

Building Economic Loss Estimation

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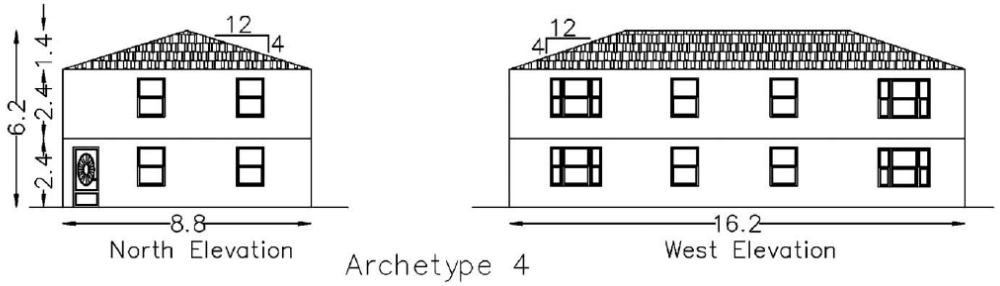

$i = 1, j = 5, \mathrm{k} = 1$

Damage State	Damage Factor(%)
None(N)	0
Insignificant(I)	5
Moderate(M)	30
Heavy(H)	68
Complete(C)	100

Calculate the estimation of loss of building at zone $i = 1$ of archetype $j = 5$ at level $\mathrm{k} = 1$ (M_{15}: appraised value of buildings for building in block 1 of archetype 5)

$$l_{151} = (P_{N|WS} \times 0 + P_{I|WS} \times 0.05 + P_{M|WS} \times 0.3 + P_{H|WS} \times 0.68 + P_{C|WS} \times 1) \times M_{15}$$

Calculate Q_{ijk}^{0}

Damage State	Damage Factor(%)
None(N)	0
Insignificant(I)	5
Moderate(M)	30
Heavy(H)	68
Complete(C)	100

$$Q_{ijk}^{0}(WS) = 1 - E[percentage\ loss\ of\ buidling]$$

$$Q_{151}^{0}(WS = 135mph) = 1 - (P_{N|WS} \times 0 + P_{I|WS} \times 0.05 + P_{M|WS} \times 0.3 + P_{H|WS} \times 0.68 + P_{C|WS} \times 1)$$

Damage state	Description
Insignificant (I)	Damage requires no more than cosmetic repair. No structural repairs are necessary. For nonstructural elements, repairs could include spackling, partition cracks, picking up spilled contents, putting back fallen ceiling tiles, and righting equipment.
Moderate (M)	Repairable SD has occurred. The existing elements can be repaired essentially in place, without substantial demolition or replacement of elements. For nonstructural elements, repairs would include minor replacement of damaged partitions, ceilings, contents, and equipment or their anchorages.
Heavy (H)	While the damage is significant, the structure is still standing. SD would require major repairs, including substantial demolition or replacement of elements. For nonstructural elements, repairs would include major replacement of damaged partitions, ceilings, contents, equipment or their anchorages.
Complete (C)	Damage is so extensive that repair of most structural elements is not feasible. Structure is destroyed or most of the structural members have reached their ultimate capacities.

(Bai et al,2009)

Strategy Cost Calculation – Building type

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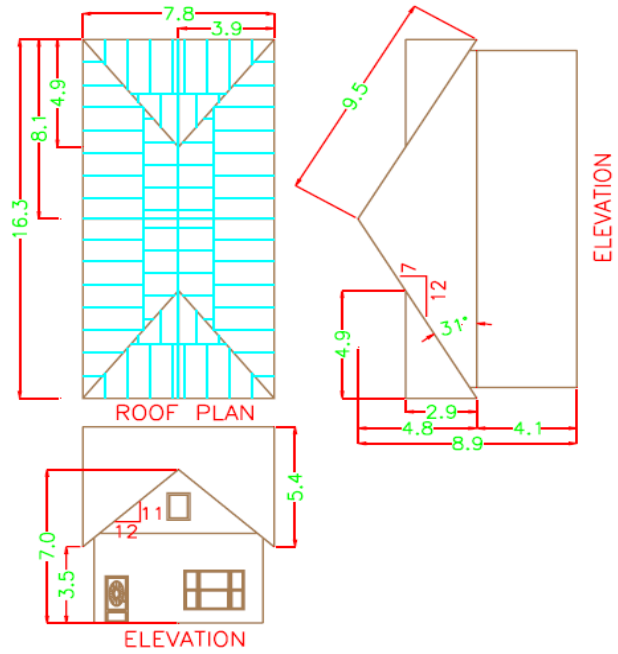
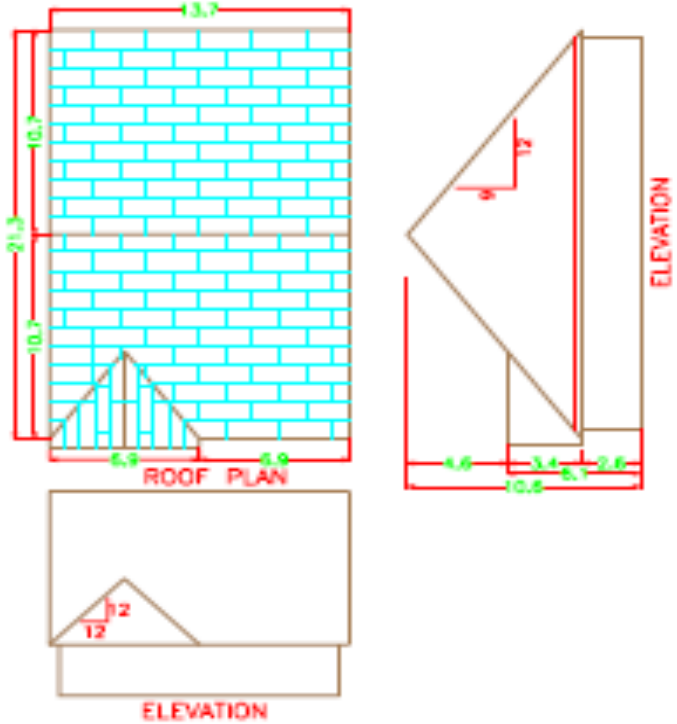


Structure Type 1



Structure Type 5

Retrofit Strategies

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Retrofit strategies	Roof covering		Roof sheathing nailing pattern		Roof-to-wall connection type		
	Asphalt shingles	Clay tiles	8d C6/12	8d C6/6	Two 16d toe nails	H2.5 clip	Two H2.5 clips
1	X	-	X	-	X	-	-
2	X	-	-	X	-	-	X
3	-	X	-	X	-	-	X

Retrofit Cost

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Retrofit Strategy	Archetype	Retrofit cost percentage (
Strategy 1	1	0.1141
	5	0.0826
Strategy 2	1	0.1733
	5	0.1434
Strategy 3	1	0.3533
	5	0.2574

The final retrofit cost =

Appraisal Value of the building * Retrofit cost percentage