Safety Assessment Method for Prefabricated Timber Roof Truss

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Abstract

Safety Assessment Method (SAM) is the mechanism used to evaluate the robustness of a structure under the event of local failure such that a progressive collapse may occurs. In this method, the sensitive and key elements are identified to ascertain the structural members that are sensitive to failure and the members that are prime to prevent the subsequent failure of the structure. The sensitive element indicates the first element to induce further progressive failure of the structure while the key element signifies the prime member of the truss that can withstand the progressive load after which a member fail. In this study, a linear static analysis of a truss structure is conducted and the sensitive and key elements are identified. Internal member forces of the truss from seven (7) cases of member failure are computed to determine the robustness of the structure. Subsequently the key and sensitive elements were computed from the result of internal member forces. A prefabricated timber roof truss of Howe configuration was used in the data analysis. The truss resistance and robustness to avoid the progressive collapse are evaluated. Results show that member 2 of the bottom chord is the major key element and member 6 of the bottom chord is the most sensitive element. However, majority of the truss members are of equally importance in the key element and sensitivity index since there is no significant differences are detected.

Keywords: *key and sensitive elements; Safety Assessment Method; truss structure's robustness; progressive collapse;prefabricated timber roof truss.*

1. Introduction

Progressive collapse behavior of a structure attributed by the unexpected loads from impact loads, earthquake and typhoon are of great interest by many researchers. The investigation of such behavior thru theoretical and experimental study however are costly and can be very complicated. Many researchers opted for numerical simulation to analyze the progressive collapse behavior. Some researchers use the finite particle method (FPM) to analyze the progressive collapse behavior [2]. For truss structures, static and dynamic analysis of progressive failure are recommended [3]. Elastic analysis with various load combinations and magnitudes will enable to correctly identify the load and failure mode of the structure. In addition, the non-linear time-history analysis will able to trace the dynamic response of rapid member snap-through behavior together with the response of the elastically designed structure. This feature provides the analysis capability of the progressive failure vibration structural response under severe earthquake dynamic loadings. For potentially catastrophic and sudden collapse of space truss structures, analysis models which closely simulate the actual structural response to loading are required.

Some building codes provide guidance to progressive collapse analysis and design. General Service Department (GSA) [4] [5] and Department of Defence Unified Facilities Criteria (UFC) [6], both from USA, currently are most complete guidelines catering for progressive collapse design [7]. Two methods are adopted in mitigating progressive collapse, i.e. (1) Direct Design approach consisting of either Specific Local Resistance Method or Alternate Load Path Method; (2) Indirect Design approach. Whilst the direct design approach requires the primary structural elements capable of resisting abnormal loadings, the indirect design requires only the minimum strength reinforcement continuity and also the ductility of structural component to resist progressive collapse [7]. Specific Local Resistance Method requires primary members of the structures such as columns and any lateral force resisting members to be designed for abnormal load, thus preventing for progressive collapse. On the other hand, the alternate path method will allow primary structural member to fail locally but not to exceed the limit of total damage such that the structure can effectively redistribute the loads and prevent any further collapse or failure.

Progressive failure of a structure is a dynamic process. Initial failure of a local structural member will cause internal force redistribution in which it may induce other members to subsequent failure. The initially failed member is considered a sensitive member. A structural member is considered a key element if the member can stop the progressive failure process by making a new stable load path in the chain reaction before the whole structural collapse.

A quantitative evaluation method to identify sensitive and key elements in truss structure is a simplified method to analyse and prevent progressive collapse behaviour. A Safety Assessment Method (SAM) adopting static analysis by which the sensitive and key element are identified proven to be practical measure in preventing progressive collapse.

2. Safety Assessment Method

The concept of key element and sensitive element are the two important parameters used in the Safety Assessment Method (SAM). The same parameters were mentioned in various guidelines [8] [9] [10]. In SAM, sensitivity analysis of linear procedure is conducted to view the changes in structural response when the initial damages or failures occur [11]. When considering the capacity loading of the structural system, JSSC [10] however extended this procedure to a nonlinear ultimate capacity analysis with significant computer time. On the other hand, GSA [5] adopted the demand-capacity ratio (DCR) using the linear or nonlinear analysis procedure. The latter not only accounted for structural loading capacity but also reduced the computer time. Sensitive element is considered the first fatal point in the original load path in which the structural loading resistance deteriorate significantly and subsequently induce the progressive failure of the adjacent member. The key element is the next fatal point to maintain or form a new load path which thus capable of achieving a robust structure. Sensitivity analysis is a linear analysis procedure that investigates the structural response changes due to initial damages or failures [11].

Figure 1 illustrated the flowchart of Safety Assessment Method provided by Jiang et.al [1]. This paper attempts to adopt the formulation provided by the flowchart in identifying the sensitive element and key element.
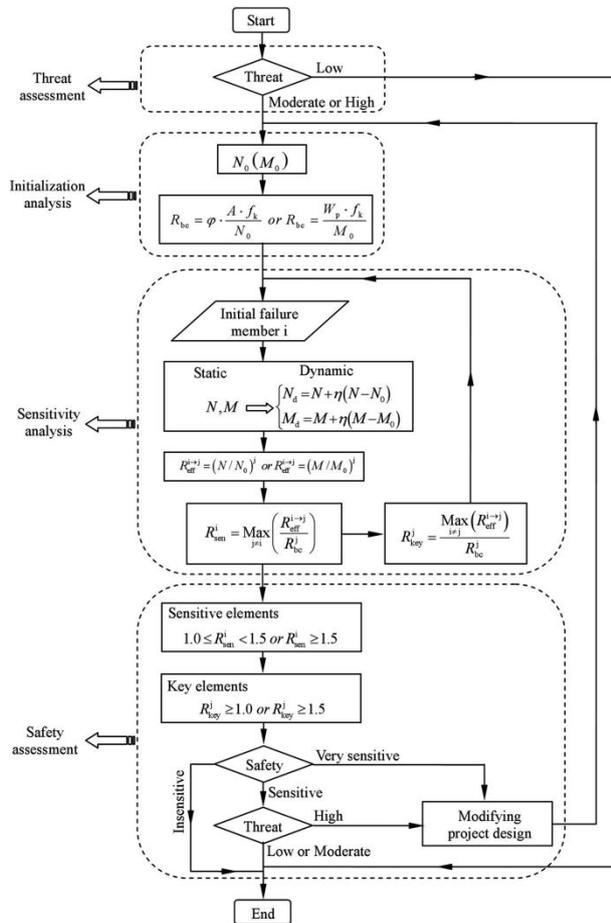

Fig. 1: Process of Safety Assessment Method [1].

The method given in the flow chart of Figure 1 is divided into four phases: (1) Threat assessment, (2) Initialization analysis, (3) Sensitivity analysis, and (4) Safety assessment phase. The threat assessment investigates the potential of an external threat and the likely initial failure of accident event. In the initialization analysis, the original load-bearing margin of the members of a structure against gravity loads are investigated. The load-bearing capacity coefficient of the members are calculated to show the potential weak part in the original system of the structure. The load-bearing capacity coefficients, R_{bc} approximately can be computed for a truss member by equation (1).

$$R_{bc} = \varphi \cdot \frac{A.f_k}{N_0} \quad \text{for truss member} \tag{1}$$

In the non-damaged condition N_0 is an axial force of a truss member under gravity load. A = area; φ is the stable coefficient for axial compression but for tension force is taken as 1.0, and f_k is definite minimum value of timber yielding strength. Based on design's safety margin, the range of 2.0 to 3.5 for load-bearing capacity coefficient of primary members is estimated.

In sensitivity analysis, the linear analysis is conducted presuming initial failures on different members. The effect coefficients of truss members in each case is calculated by using equation (2)

$$R_{eff} = \frac{N}{N_0} \qquad \text{for truss member} \tag{2}$$

N is axial force of truss members in the remaining structure after initial failure and is computed by using the linear static analysis. In general, the effect coefficients of primary members commonly exceed 2.0, even 5.0 after initial failure. The sensitivity index of initially failed members, R_{sen}, is defined as the maximum value of residual elements' demand-capacity ratios by using Eq. (3). That is to say that the sensitivity index of a given member i is specified by all the remaining members j. The key index of a residual element j, R_{key}, however, is defined as the maximum value of its demand-capacity ratios by each possible initial failure of other members, by using Eq. (4).

$$R_{sen}^i = \max_{j \neq i} \left(\frac{N}{\varphi.A.f_k} \right)^j \tag{3}$$

$$R_{key}^j = \max_{j \neq i} \left(\frac{N}{\varphi.A.f_k} \right)^j \tag{4}$$

Theoretically, it is reasonable to identify all members with $R_{sen} > 1:0$ as sensitive elements. Considering the existence of the energy dissipation capacity of primary and secondary members, members only with $R_{sen} > 1:5$ are considered to be actual sensitive elements or very sensitive elements in this study. Likewise, key elements are those only with $R_{key} > 1:5$. The key and sensitivity index can also be uniformly defined as follows:

$$R_{sen}^i = \max_{j \neq i} \left(\frac{R_{eff}^{i \rightarrow j}}{R_{bc}^j} \right) \tag{5}$$

$$R_{key}^j = \frac{\max_{j \neq i}(R_{eff}^{i \rightarrow j})}{R_{bc}^j} \tag{6}$$

Where R_{bc}^j means the load-bearing capacity coefficient of residual member j and $R_{eff}^{i \rightarrow j}$ represents the effect coefficient of member j due to initial failure of member i.

3. Truss and Loading Configuration

A pre-fabricated timber roof truss was used as a case study. The truss configuration and the loading arrangement for the study is shown in Figure 2. The members are numbered starting from the bottom chord (member 1 to 4), followed by the top chord (member 5 to 8), then the vertical chords (member 9 to 11) and finally the diagonal chord (member 12 and 13). Point load of 0.570 kN was applied at node points at the top chords. The size of all members is 38 mm x 73 mm. StaadPro software was used to determine the internal forces of the member under the specified loadings.
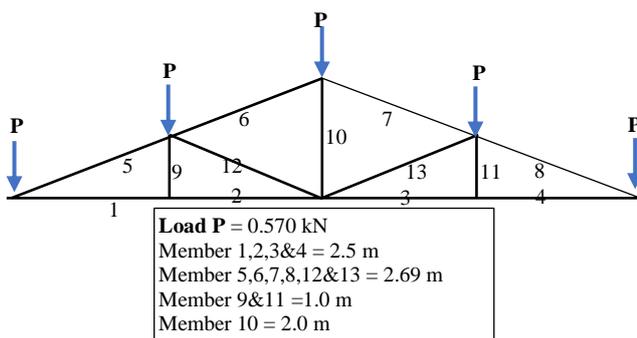

Fig. 2: Truss dimension and loading configuration

3.1. Analysis

Internal member forces were analyzed based on 7 cases of member removal as shown in Table 1. Different member will be removed from the truss for every case assuming that the member fail which induced the progressive collapse behaviour. Case 0 is the control case where all members remain intact.

Table 1: Implemented Cases in Analysis

Cases	Member Removal
Case 0	No member removal
Case 1	Member 1 removed

Case 2	Member 2 removed
Case 3	Member 5 removed
Case 4	Member 6 removed
Case 5	Member 9 removed
Case 6	Member 12 removed
Case 7	Member 10 removed

3.2 Results and Analysis

Table 2 tabulate the results of internal member forces of each case whilst Table 3 presented the largest internal load for each member in relation with the cases. Subsequently, the load-bearing capacity coefficients R_{bc} and the effect coefficients R_{eff}, were further computed (in Table 4) from the equations described earlier. Table 5 and 6 tabulate the results of the key index Ri_{key} and the sensitive index R^i_{sen} of the truss member, respectively. The sample calculations of the respective parameters are provided accordingly. Table 7 tabulate the key index sequence whilst Table 8 tabulate sensitive index sequence. Both tables ranked the truss members from the most sensitive to least sensitive.

Table 2: Axial forces of each member of all cases in kN

Member	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
1	1.650	-	1.349	-	1.829	1.663	1.579	1.631
2	1.646	0.992	-	1.355	2.560	1.663	1.286	1.540
3	1.646	1.615	1.550	1.622	2.130	1.648	1.605	1.540
4	1.650	1.644	1.631	1.645	1.746	1.650	1.642	1.631
5	1.851	0.382	1.685	-	2.031	1.870	1.777	1.848
6	1.278	1.286	1.385	1.364	-	1.271	1.361	1.129
7	1.278	1.312	1.403	1.323	0.465	1.274	1.332	1.129
8	1.851	1.846	1.834	1.845	1.956	1.851	1.844	1.848
9	0.340	0.131	0.214	1.295	0.844	-	0.226	0.085
10	0.545	0.309	0.139	0.693	0.517	0.540	0.459	-
11	0.340	0.046	0.098	0.069	0.553	0.030	0.062	0.085
12	0.557	0.164	1.373	0.120	2.526	0.585	-	0.408
13	0.557	0.473	0.314	0.512	1.595	0.563	0.454	0.408

Table 3: The largest internal load for each member

Member	Axial Load (kN)	Cases
1	1.829	4
2	2.560	4
3	2.130	4
4	1.746	4
5	2.031	4
6	1.385	2
7	1.403	2
8	1.956	4
9	1.295	3
10	0.693	3
11	0.553	4
12	2.526	4
13	1.595	4

Calculation of R_{bc} and R_{eff}

Apply equation (1) of Safety Assessment Method

$$R_{bc} = \varphi \cdot \frac{A.f_k}{N_0} \quad \text{for truss member} \tag{1}$$

$= 1$
$= 38mm \times 73mm = 2774mm^2$
$f = 1.0$ Nmm² (Assume is 1, because the same material is used for all members)

Calculation of R_{bc}^2
$$R_{bc}^2 = \varphi \cdot \frac{A.f_k}{N_0} = 1 \cdot (2774mm^2)(1N/mm^2)/1.646kN = 1(2774mm^2)/1.646(1000)N = 1.685$$

Apply equation (2) of Safety Assessment Method

$$R_{eff}^{i \to j} = \frac{N}{N_0} \text{ for truss member} \tag{2}$$

Calculation of $R_{eff}^{1 \to 2}$
$$R_{eff}^{1 \to 2} = \frac{N}{N_0} = 0.992kN/1.646kN = 0.602$$

Table 4: Value of R_{bc} and $R_{eff}^{i \to j}$

		$R_{eff}^{i \to j}$						
		Case						
Member	R_{bc}	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1	1.681	0.000	0.817	0.000	1.108	1.007	0.957	0.988
2	1.685	0.602	0.000	0.823	1.555	1.010	0.781	0.935
3	1.685	0.981	0.941	0.985	1.294	1.001	0.975	0.935
4	1.681	0.996	0.988	0.997	1.058	1.000	0.995	0.988
5	1.500	0.206	0.910	0.000	1.097	1.010	0.960	0.998
6	2.170	1.006	1.083	1.067	0.000	0.994	1.065	0.883
7	2.170	1.026	1.097	1.035	0.364	0.997	1.042	0.883
8	1.500	0.997	0.991	0.996	1.056	1.000	0.996	0.998
9	8.158	0.385	6.294	3.811	2.482	0.000	0.665	0.250
10	5.101	0.567	0.255	1.271	0.948	0.991	0.842	0.000
11	8.158	0.135	0.288	0.203	1.626	0.088	0.182	0.250
12	5.100	0.294	2.465	2.011	4.535	1.050	0.000	0.732
13	5.100	0.850	0.564	0.920	2.863	1.011	0.815	0.732

Calculations of R_{key}^{j} and R_{sen}^{i}

Apply equation (6) of Safety Assessment Method

$$R_{key}^{j} = \frac{\max_{j \neq i}(R_{eff}^{i \to j})}{R_{bc}^{j}} \tag{6}$$

For member 1, $\max_{j \neq i}(R_{eff}^{6 \to 1}) = 1.108$; $R_{bc}^{1} = 1.681$;
$R_{key}^{1} = 1.108/1.681 = 0.660$
For member 1, $\max_{j \neq i}(R_{eff}^{6 \to 2}) = 1.555$; $R_{bc}^{2} = 1.685$;
$R_{key}^{2} = 1.555/1.685 = 0.923$

Table 5: The Key index (R_{key}^{j}) of truss member

Member	**R$_{bc}$**	**Max$_{i \neq j}$(R$_{eff}$$^{i \to j}$)**	**R$^{j}_{key}$**
1	1.681	1.108	0.660
2	1.685	1.555	0.923
3	1.685	1.294	0.768
4	1.681	1.058	0.630
5	1.500	1.097	0.731
6	2.170	1.083	0.510
7	2.170	1.097	0.505
8	1.500	1.056	0.704
9	8.158	6.294	0.771
10	5.101	1.271	0.250
11	8.158	1.626	0.210
12	5.100	4.535	0.301
13	5.100	2.863	0.561

Calculations:

Apply equation (5) of Safety Assessment Method

$$R_{sen}^{i} = \max_{j \neq i}\left(\frac{R_{eff}^{i \to j}}{R_{bc}^{j}}\right) \tag{5}$$

For case1, member 1 removed, so i =1,
$R_{sen}^{i} = \max_{j \neq i}\left(\frac{R_{eff}^{1 \to j}}{R_{bc}^{j}}\right) = 0.665$,   is the largest value of $(R_{eff}^{i \to j}/R_{bc}^{j})$ in case 1 amongst members which is in member 8.

Table 6: The Sensitive Index (R_{sen}^{i}) for each removed member

Case	**Removed member i**	**R$^{i}_{sen}$**
1	1	0.665
2	2	0.771
3	5	0.664
4	6	0.923
5	9	0.673
6	12	0.664

7	10	0.665

Table 7: The Key Index Sequence

Sequence	Member	Key Index	Sensitivity
1 **Most sensitive**	2	0.923	High
2	12	0.890	High
3	9	0.771	High
4	3	0.768	High
5	5	0.731	High
6	8	0.704	High
7	1	0.660	Moderate
8	4	0.630	Moderate
9	13	0.561	Moderate
10	6	0.510	low
11	7	0.505	low
12	10	0.250	low
13 **least sensitive**	11	0.210	low

Table 8: The Sensitive Index Sequence

Sequence	Member	Sensitive Index	Sensitivity
1 **Most sensitive**	6	0.923	High
2	2	0.771	Moderate
3	9	0.673	Moderate
4	1,10	0.665	Moderate
5 **least sensitive**	5,12	0.664	Low

3.3 Discussion

From Table 3, case 4 (i.e. where member 6 removed) has induced a lot of members with highest internal member forces. Member 1 to 5, 8, and 11 to 13 were affected in having higher internal forces when member 6 of the top chord is removed or presumably failed due accidental event. The highest internal member force is on member 2 of the bottom chord which is at 2.56 kN due to this removal. Case 2 (i.e. where member 2 removed) has affected member 6 and 7 (both from top chords) to have highest internal force whilst Case 3 (i.e. where member 5 removed) has affected member 9 and 10 (both from vertical chords) to have highest internal force. For Case 2 and 3, the highest internal member force is 1.403 kN from member 7 and 1.295 kN from member 9, respectively.

Figure 4 illustrate the results presented in Table 5 on key index and Figure 5 summarize results from Table 6 on sensitive index. As discussed in Section 2.0, sensitive element is considered the first fatal point to induce the progressive failure of the adjacent member whilst key element is the next fatal point to sustain the failure. Reasonably, any members with $R_{sen} > 1:0$ is sensitive elements. Likewise, key elements are those only with $R_{key} > 1:5$.

From Figure 4, none of the truss member has a key index more than 1.5. The key index ranges from 0.210 to 0.923 with majority of the members in the range of 0.5 to 0.7. The highest key index is from member 2 of the bottom chord with $R_{key} = 0.923$ followed by member 12 ($R_{key} = 0.890$) of the diagonal bracing. This indicator shows that all truss members play equally a key role in preventing the progressive failure of the whole structure where member 2 and 12 perform a higher role in sustaining the load.

Similar pattern was observed in the sensitive index as shown in Figure 5. Again, none of the member has the sensitive index of more than 1.0. The sensitive index ranges from 0.664 to 0.923 in which the highest is from member 6 of the top chord whilst the lowest is from member 5 (top chord) and 12 (bracing member). Thus, the pattern shows that majority of the truss members are equally sensitive to failure and will induce progressive collapse to the adjacent members of the truss. All in all, it is observed that member 2 of the bottom chord is the main key index for the truss whilst member 6 of the top chord is the most sensitive member.
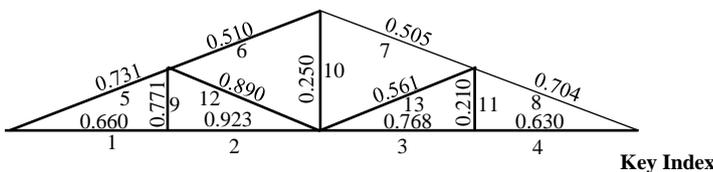

Key Index
Fig. 4: Diagram shows the most key index members
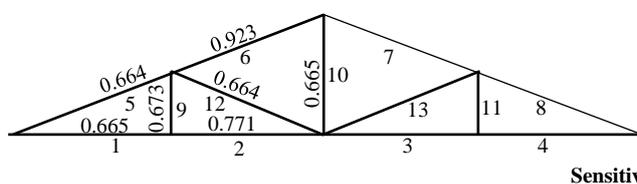

Sensitive Index
Fig. 5: Diagram shows the most sensitive index members

4. Conclusion

Safety Assessment Method may be the best tool to evaluate the robustness of the truss structure. The above parametric study indicates that most members play an equally important role as key and sensitive members of the truss. Further study can be conducted to other types of truss configuration and to evaluate whether similar behaviour pattern can be observed. Nevertheless, the behaviour pattern of these key and sensitive elements should be further verified through the experimental result.

Acknowledgement

The authors would like to thank the University for providing the facilities to conduct the research.

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