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Review of Numerical Methods for Analyzing the Progressive Collapse of Concrete Structures

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Abstract: Construction accidents have been documented throughout history. One type of failure mechanism is progressive collapse, in which one or more structural components fail suddenly without regard to the cause (attack, anomalous accident). Numerous methods have been employed to simulate the impacts of this phenomenon. Still, they are all predicated on some distinct premises, such as the procedure's independence from the root cause of the first failure or the order in which the pressures are applied. To analyze framed building structures in the event of a column loss caused by an extreme event, this paper evaluates and offers an overview of the numerical analytical tools and approaches that are now available. In the literature, there has been a discussion of the applied element method, the discrete element method, and the finite element method. They were thoroughly discussed and contrasted. This study investigates and ends with challenges that must be resolved in many areas that will be required in the future.

Keywords: Progressive Collapse, Structural Failure, Frame Structures, Extreme Events, Analytical Tools, And Numerical Studies.

I. INTRODUCTION

When a building's column is removed, the weight it supports is dispersed among the nearby slabs, beams, and columns until the structure's balance is restored. If the elements are not intended to spread the weight, a disproportionately large section of the building may collapse. This type of structural failure is known as "progressive collapse" (Nair, 2004). It occurs when a full structure or a portion of a structure collapses as a result of a small or local building collapse. Localized action triggered through an accident, a danger, or local loss of strength owing to design or construction defects, age, or outside influences can initiate progressive collapse. Because of their probability of occurrence and design code, these are referred to as incidental occurrences. exhibit numerous circumstances that can emerge in the framework, enabling the structural robustness to be tested. (ii) unexpected and erroneous occurrences in the building, might be classified as column removal (Starossek, 2017). Figure 1 depicts the partial fall of Ronan Point in London, UK, in 1968. the progressive collapse has received much attention in recent years. The whole southeast corner collapsed due to a gas leak (Griffiths et al, 1968). The scientific engineering community quickly grasped this phenomenon. Another such instance, according to the Department of Defense (DOD), happened in 1986 when the New World Hotel in Singapore collapsed as a result of a human error (the change in the self-weight of the structure was not addressed by the design team) (DoD, 2009). Gradual collapse can occur in several ways, they are classed depending on the major force applied to the failing portions and the direction of failure propagation. Gradual collapses of the pancake, zipper, domino, section, instability, and mixed types are among them (Starossek, 2009). Progressive collapse may take place by a variety of mechanisms and types. The vast bulk of recent studies. however, is focused on redistribution-type progressive collapse (Starossek, 2017). Flat slab structures frequently feature pancake and zipper joints. When one structural element collides with another, it fails, and the process is repeated with subsequent lower-lying components, resulting in vertical failure propagation. The Sampoong Department Store catastrophe resembled a pancake-shaped progressive collapse, as shown in Figure 2.

The zipper-type failure, in contrast to the pancake-type failure, has both a path of breaking transmission and the location of the main force in failing components operating in the same direction (usually in the direction of gravity). Failure spread is frequently horizontal. Following such an initial punching, subsequent punching of neigh boring slab-column connections results in a zipper-type progressive collapse, as demonstrated in the partially collapsed Pipers Row Car Park (Ulaeto, 2018).

Unexpected, exceptional forces that hadn't been planned throughout the design phase produced the problem. These loads include pressure and impact gas explosions, blasts, airplane impacts, earthquakes, and fire. For a progressive collapse to spread, three factors must be met: local components failure, loss spreading to additional components, and an eventual collapse disproportionate to an initial failure. The earliest studies on delaying progressive collapse were undertaken in 1970 (Leyendecker et al., 1977). For example, the blast-induced single-column loss is one possible avenue for zipper-pancake formation, as shown in Figure 4 (Kiakojouri et al, 2020).

Figure 1: The progression of the collapse of the Ronan Point condominium in London, United Kingdom (Pearson and Delatte, 2005).
Figure 2: The failure of the s department store in Seoul, South Korea (Gardner et al, 2002).

II. THEORETICAL ANALYSIS

Progressive collapse is investigated using analytical, experimental, or computational methods, much like any other structural engineering subject. However, because collapse is a nonlinear, dynamic process that requires precise management during the test, experimental examinations are frequently costly and harmful. As a result, numerical approaches are preferred by academics to understand better the underlying process of stepwise collapse (Kiakojouri et al, 2020).

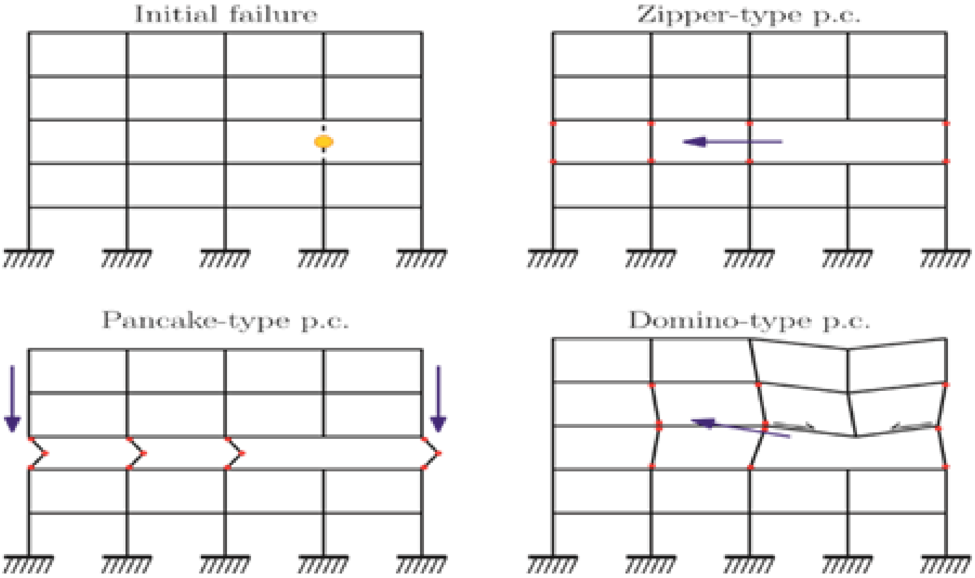

Figure 3: Illustrations of the most common propagation types found in frame structures., p.c (progressive collapse) (Kiakojouri et al, 2020)

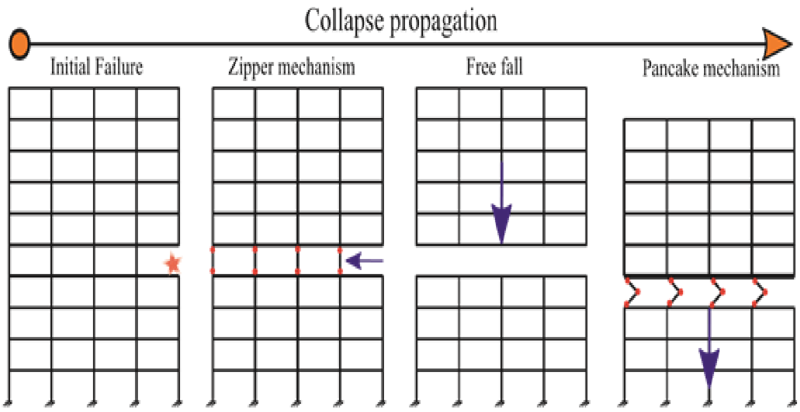

Figure 4: Illustrates a mechanism for zipper-pancake collapse (Kiakojouri et al, 2020).

The two primary methods of numerical progressive collapse research are the finite element method and the applied element method. Others, in contrast, use the discrete element method (DEM). ABAQUS, LS-DYNA, and DIANA are examples of general-purpose finite element analysis tools. Special building FEA software of varying complexity is also being considered, with fiber-based models OpenSees and SAP2000 research projects offered. The investigators used the Extreme Loading for Structures (ELS) tool while addressing the applied element method (AEM). When using FEM to examine step collapse, modeling, and simulation often make use of exhaustive and simplifying assumptions. The majority of researchers used 2D models using beam elements; however, with increased processing capacity, 3D finite element models are now conceivable. Overall, 2D representations can provide acceptable assessments, particularly if the loss is unexpected. Due to the absence of three-dimensional effects and force transmission in slabs, 2D representations display higher deformations (Alashker et al., 2011). In addition, incorporating slab effects improves flexural and arch action abilities; hence, 3D and slab effects should not be ignored for efficient progressive collapse evaluation and design. In contrast, 2D models may be effective for early assessment and contrast of alternative situations (Qian et al., 2015). The global response of beam component models can be comparable to the response of shell or solid models when utilizing the finite element method (FEM) and at the element level, as explained in Liu (2010).

The complete structure, a substructure, or a single component and connection can When modeling the entire system, beam-type elements are used for beams and columns, and shell-type elements are recommended for slabs, while shell- or solid-type elements are utilized for modeling members or connections in a micro model. Some investigations employed a multiple-scale model where sections around a damaged zone were more precisely copied using solid or shell components, whereas different components were rebuilt with beam components (Li and Hao, 2013; Le, J. L., and Xue, 2014). (Botez et al, (2016) describe another bay reduction-based simplification technique. Such assumptions are typically unneeded, and because of the unique nature of AEM, a comprehensive 3D model may be produced easily (Grunwald et al, 2018). The bulk of numerical research is on braced frames, as well as steel and RCC moment-resisting frames. AEM and DEM are the finest alternatives for collapse sequences. The finite element method (FEM) method assumes the structure to be a linked system that must maintain balance. Artificial and coercive operations, such as element removal, are required in part separation and free-fall scenarios, rendering the FEM unsuitable for analyzing the falling dynamics of frame construction. FEM is unable to forecast the process and sequence of collapse, particularly at the last stage. Other building failure analysis computational approaches, such as the cohesive element method (CEM) (Xue and Le, 2016) and smoothed-particle hydrodynamics (SPH) (Xu and Liu, 2008), are rarely used. These techniques have been omitted from further examination because of a lack of credible literature, and the emphasis in the following sections is on the finite element method, applied element method, and discrete element method as the three basic procedures for progressive collapse analysis. Figure 5 depicts the contrast between three distinct strategies. There are at least five resistance mechanisms against the gradual collapse of frame-building systems, as illustrated in Figure 6. Initially, the flexural behavior of the beams directly above the damaged components Figure 6a allowed distributed loads due to local failure to exist. Larger displacements can be predicted to exhibit Vierendeel Figure 6d and Arch Figure 6b tendencies. Catenary movements Figure 6c is often regarded as the last level of resistance in structured constructions, avoiding gradual collapse (Kiakojouri et al, 2020).

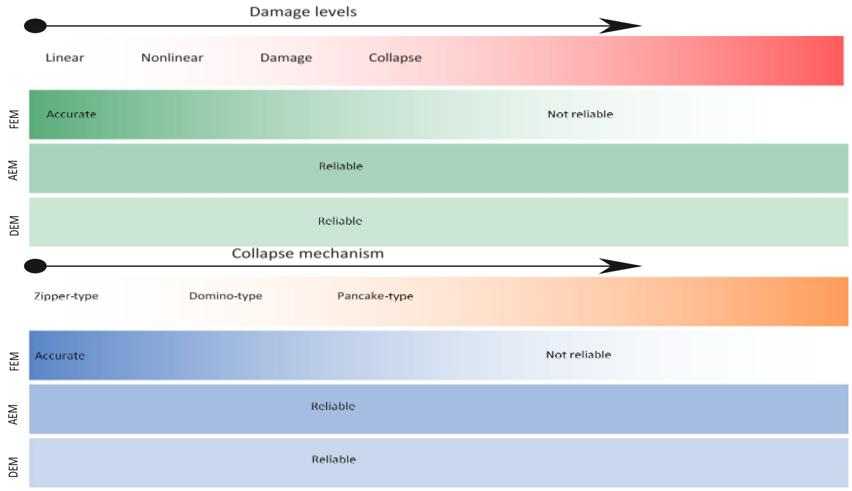

Figure 5: FEM and AEM comparison at various damage stages (Kiakojouri et al, 2020).

III. TYPES OF NUMERICAL INVESTIGATIONS

1) Finite Element Method

All the explicit and implicit finite element methods (FEM) can be used for failure analysis in building systems because they can predict the progressive collapse potential (Qian et al, 2021). Looking for alternate load paths is a risk-free method that focuses on the structural response to local failure rather than the triggering event. The alternate load path (ALP) technique may be utilized to do progressive collapse analysis statically or dynamically, and nonlinearity can be taken into account or disregarded. Nonlinear static (pushdown) analysis has long been the standard, although nonlinear dynamical analysis is used for progressive collapse analysis, which is gaining popularity. The researchers provide many methods for removing numerically dynamic columns. The first force-based approach was invented and popularized by (Tavakoli and Kiakojouri, 2013).

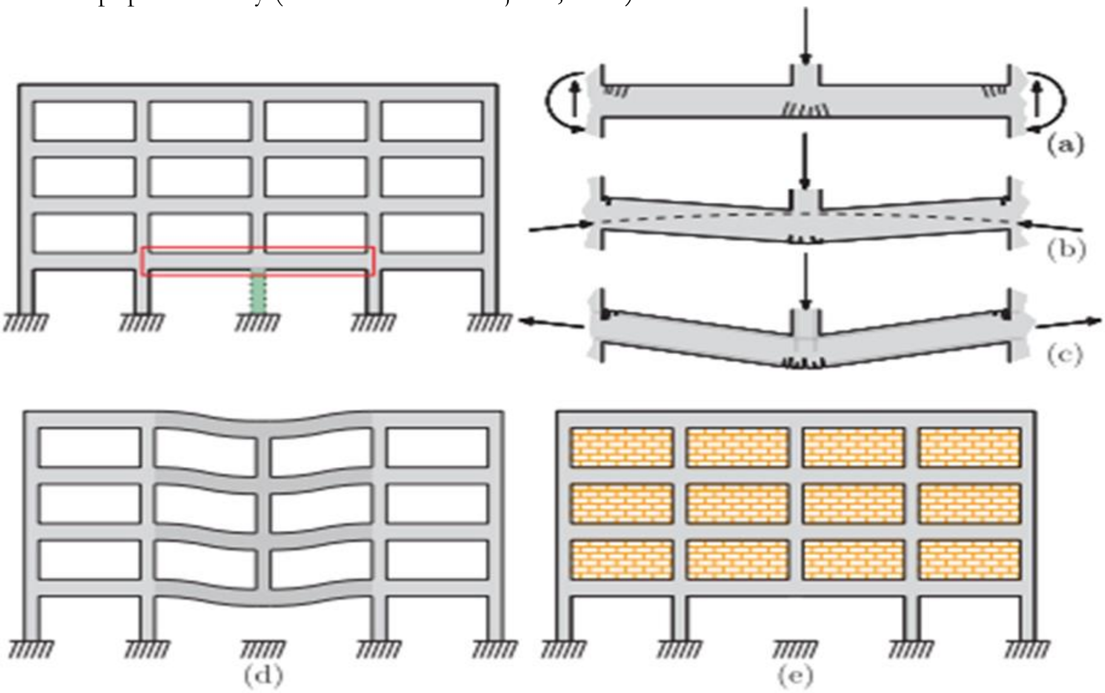

Figure 6: Strategies to avoid redistribution-type collapse in cascading collapses of concrete buildings include, in order, bending, arch behavior, catenary behavior, Ferndale behavior, and non-structural contributions (Kiakojouri et al, 2020).

This approach is straightforward to use and may be used in practically any FEA package.

As a result, we have three broad modeling objectives. Phase 2: the adaptive spread of plasticity; Phase 3: global softening; and Phase 4: the catenary dynamic state

Each of these objectives includes sub-discrete needs that will influence the evaluation and development of the computer modeling regime. The table

below (Hatahet, 2018) summarizes this. Table 1 presents a summary of the modeling goal of the disproportionate collapse of RC assembly.

Table 1. A summary of the modeling aim of disproportionate collapse

Target 1; Phase II: the adaptive spread of plasticity
1. The strain at which hardening in steel begins
2. Large geometrical displacement
3. Modes of failure in RC columns
4. Shear interaction in shear critical elements
Target 2; Phase III: the global softening
1. Buckling of compressive reinforcement.
2. Post-peak concrete damage and failure.
3. The lowermost strength at point D
Target 3; Phase IV: the dynamic state of catenary
1. The strain rate effect, or the dynamic force increase factor.
2. Model of steel in hardening and softening.
3. Model the transition and the dynamic amplification factor

Figure 7 depicts a response curve that has been idealized. The graph depicts the change in response force caused by raising the displacement at the missing column point in a quasi-static way. The response curve should contain four characteristics.

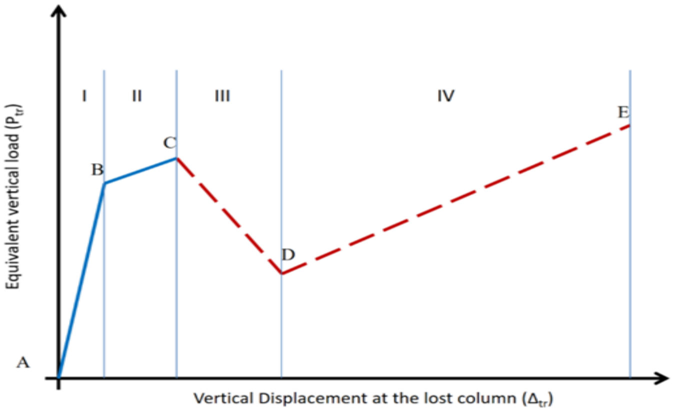

Figure 7: illustrates the change in response force caused by a quasi-static displacement increase at the missing column point (Hatahet, 2018).

When a major load-bearing element fails or must be replaced, linked spans deflect when the rotational capacity provided by surrounding beams or slabs is depleted. As a result of the catenary movement, the beam may be able to carry vertical loads over long distances. This is referred to as "catenary action" (Alogla, 2017).

The presented simulation tactics according to finite element methods may be classified depending on the software utilized and the category of solution processes used. We can classify the following:

Damage models that use detailed dynamic simulation and element wear functions are examples of LS-Dyna (Bao et al, 2014) and MSC-MARC (Lu et al, 2011). The necessity for a modest time-integration step is a typical concern with explicit methods; nevertheless, when the robustness of the integration surpasses this disadvantage without producing convergence issues, this alternative becomes more tempting (Lu et al, 2013). Target 1 cannot follow the whole evolution of the collapse mechanism, unlike the gradual collapse model's identified goals, Because the coexistence of plastic deformation, hardening, and softening at various points in the model's structure makes explicit integration impossible, an implicit time solution step is required before the algorithm transitions from the solid to the flowing state. Even though a collapse mechanism is specified in the case of building denotation, researchers acknowledged this constraint and employed hybrid simulation to track the local plastic deformation at sectional levels (Hartmann et al, 2008). The quality of the indicated failure mechanism is lacking at the final point. Despite this, it remains an appealing and extensively used continuum discontinuous modeling technique. As a result, while this simulation may forecast strength in the 'phase II' objective, it will undermine the aims of 'phase II,' prohibiting the correct prediction of ductility. This simulation strategy is ideal for the objectives of phases 'III and IV' because it describes the state of motion naturally using well-established Newton's laws (Hatahet, 2018).

Using simplified (macro) models for explicit dynamic analysis In contrast to the preceding, more general class, this class of models seeks to lower the computing cost of the continuum elements. The use of macro-elements involves some preprocessing to compute their corresponding attributes. This fact decreases the modeling's quality even more since it obscures the change in material behavior induced by the unavoidable change in the loading state. In contrast, the material's physical characteristics vary during the simulation. As a result, this becomes more difficult in stages I and II (Hatahet, 2018).

an implicit quasi-static analysis with an element erosion function for damage simulation. As shown in (Sasani et al, 2011) and (Lu et al, 2011), examples include ANSYS, ATHENA, ABAQUS, and DIANA. Aside from the advantages of adaptive time stepping, utilizing an implicit integration technique enhances the prediction of the collapse process. As a result, these are among the best. As a result, these are the most outstanding options for meeting both Targets 1 and 2. However, there are three distinct disadvantages:

The full model of the structure remains beyond practical implementation due to the size of the unknowns, as well as the convergence difficulties associated with a continuum implicit integration scheme and volumetric locking problems, and is therefore not suggested for the robustness and sensitivity analysis proposed in the previous section.

Material failure is modeled using element erosion criteria that are based on local finite element factors (deformations), in addition to the necessity for full geometrical modeling of the steel reinforcement and the suitable bond and slide behavior of the reinforcement. Because the error is usually controlled at the model level, these local variables have a higher error order, undermining the reliability of the progressive fail simulation, particularly if the erosion function depends on the failure mode and strain rate, requiring customized configuration at different locations (Hatahet, 2018).

Implicit quasi-static simulation using Open SEES, SeimoStruct, and SAP2000 based on reduced (macro) models, e.g. (Li et al, 2013). These models profit from the problem's modest number of unknowns. The models described in the literature, on the other hand, are validated only after the arching point. As a consequence, while it may be a decent approximation for the ultimate strength phases 'I and II', it is not the best for the collapse progression analysis as stated in phases 'III and IV'. The supplied models are only valid for the elastic response of the mechanism and do not provide full validation of target 1. To the best of our knowledge, the provided models are only viable for the dynamic modeling of the mechanism's elastic repose (Hatahet, 2018).

Ls-Dyna and FEAB are multi-simulation platforms based on explicit integration techniques (Lu et al, 2011). The proposed application, in principle, eliminates the necessity for implicit integration and aggregation of the response force in plastic hinges. This is only plausible if the failure mechanism is specified, as such a technique cannot identify the new position of a new plastic hinge. However, these positions have been suggested in the published model (Hatahet, 2018).

Sub-structured hybrid simulation, for example, is based on implicit integration techniques (Li et al, 2013). For example, the provided model cannot forecast the horizontal spread of the mechanism, resulting in a soft story. As a result, target 1 is missed by the model (Hatahet, 2018). The finite element method (FEM) is the most sophisticated and well-established approach for tackling nonlinear problems. It is regarded as a boundary element method (BEM) extension. Regardless of the goals stated above, the conventional FEM faces the following challenges: Gradual cracking or softening, fracture or crush of pressurized concrete, and tension bar rupture all necessitate material discontinuity simulation. Localizations induce severe mesh distortion, especially when creating a large building model with a reasonably thin mesh.

The large deformation in the collapse issue poses extra hurdles to FEM models. due to the stiffness matrix being unbalanced, they are demanding additional iteration loops in the solver.

Because of the transit nature of the elements' overall damage, there is a requirement for artificial procedures to balance eliminated pressures caused by deleted (eroded) pieces.

Before getting into other formulation techniques, it is necessary to analyze the shortcomings of standard FEM in progressive collapse modeling. While the drawbacks of the explicit approaches have already been acknowledged, the development of an implicit solution is expected to enhance the FEM (Alogla, 2017).

Dealing with progressive collapse necessitates that the FEM model address the following issues in terms of solution algorithms: The material's nonlinear behavior at the section level P-delta geometric nonlinearity and cable/catenary tensile behavior Large displacements and material flows are created until full catenary motion is achieved. Many nonlinear simulation techniques for RC beam behavior were employed in the literature, for example, in one of the most notable studies (Hatahet and Könke, 2014). Given the benefits of being simplified because of the time restrictions of this study and the models in parametric analysis, the structural FEM was chosen to describe the problem. (Talaat, (2007) provided a well-structured assessment of the topic.

The structural FE community has extensively studied both displacement-based (DB) and flexibility-based (FB) FEM structural beam/column formulations for the seismic response modeling of the structure under both static and dynamic stresses. Section analysis is the process of analyzing how a section responds to an axial load and bending moment on a known fiber base beam or column element (FibE). The uniaxial (1D) stress-strain curve of the steel and concrete at the section level serves as the foundation for the FibE when utilizing an inelastic 1D material model. As it was applied in the FB beam formulation, the notion of inelastic FibE drew even more interest. The benefit of the flexibility-based (FB) beam element over the displacement-based (DB) beam element is that force equilibrium is rigorously satisfied at the section and element levels, which lowers the DB element's convergence difficulties. However, even at the section level, FB does not offer a complete physical description of material deformation.

As a consequence, the evaluated deformation is virtual, and equilibrium must be constructed and updated as the massive displacement grows (Filippou and Fenves, 2004). According to the work of (Crisfield, 1990; Crisfield, 1991), extensions to the FB were created for high displacement and geometric nonlinear response based on the co-rotational beam element formulation (Alemdar et al, 2005). While entire FEM simulation systems based on flexibility-based FEM are uncommon, methods for incorporating FB into displacement-based FEM programs have been developed. Furthermore, in the majority of displacement-based FE codes, A well-known alternative is the flexibility-based (FB) beam/column element. To include the flexibility-based (FB) program in the displacement-based (DB) program, element flexibility must be translated into stiffness, which is commonly done by taking the inverse of the FB flexibility values (Taucer, 1991). Since the nonlinear simulations predict the plastic response of the RC part, the plastic hinge's localization can be estimated using either the lumped plasticity approach or by locating the plastic zone at the anticipated location of the expanding hinge. Despite providing a good computational solution and being validated by several calibration tests, this lumped plasticity decouples the automatic coupling of axial-benign forces. By defining the length of the plastic hinge in conjunction with the use of the FibE, the axial-bending interaction may be automatically accounted for while a specific regulatory procedure is supplied (Scott and

Hamutçuolu, 2008). A hybrid method is a zero-FibE beam element implanted at the end of an elastic beam element. A zero-FibE beam element implanted at the end of an elastic beam element (Valipouret al, (2013) bridges the gap between the two methods. This type of compromise includes component duplication and system softness issues that need further calibration.

A more realistic formulation was based on a preset length of the plastic hinge based on empirical value or standard guidelines; nevertheless, this compromises the worth of the axial-bending interaction at the crucial sections. However, in a cumulative collapse scenario, the zone of plastic hinge expands until failure and local unloading occur. As a result, the plastic hinge's growth and expansion affect the simulation's continuing development of the collapse mechanism. (Almeida et al, 2012; Lee and Filippou, 2009) recently proposed ways for expanding the plastic hinge, but none of them considered length evolution as a natural output of the simulation.

B. Applied Element Method

The AEM blends the advantages of discrete approaches with the strengths of continuous FEM formulation. It was developed to solve the limitations of FEM (Meguro and Tagel-Din 2000). The method's core idea is to describe the structure using tiny cubically stiff parts connected along their surfaces by a collection of normal and shear springs connecting small cubically rigid pieces along their surfaces. In contrast to the FEM, deformations are estimated at connecting springs rather than inside components Figure 8. The AEM offers various benefits over the FEM, including the ability to link coarsely and finely discretized model sections via springs, omitting the need for transition components. Components do not have to share their borders, and this is built into the technology, making it ideal for collapse modeling. They are assigned to the springs in the AEM approach rather than the components in the FEM method (Grunwald et al, 2018).

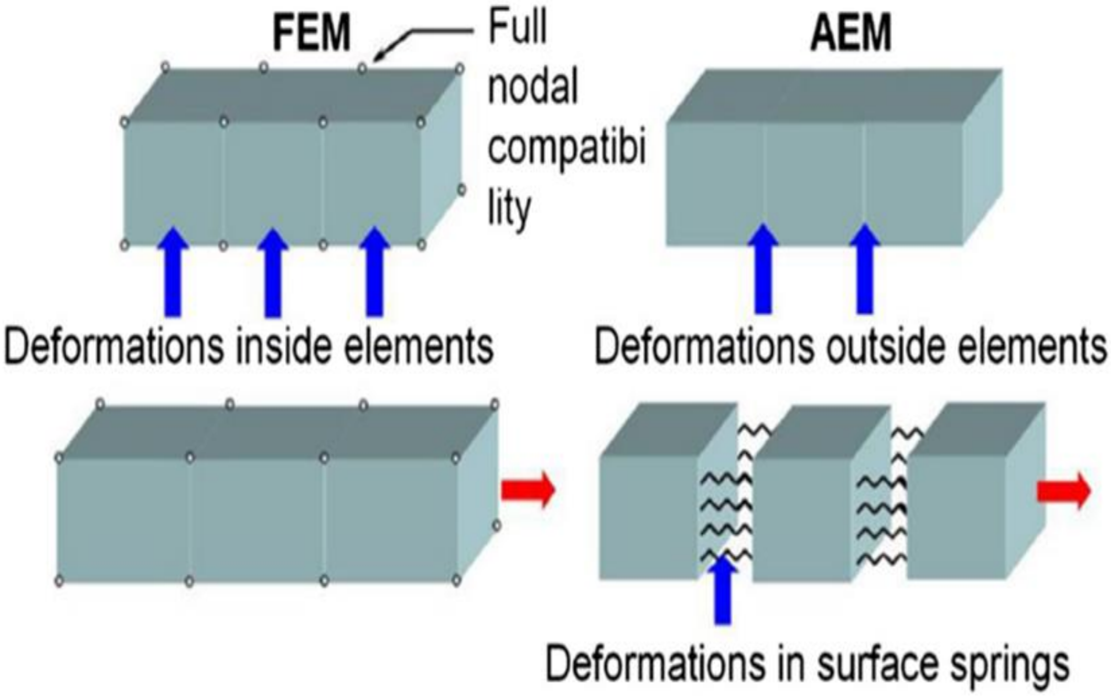

Figure 8: difference in distortions in FEM and AEM (Grunwald et al, 2018).

Finally, large-time steps are possible using the implicit integration strategy. When combined with an efficient description of the problem, this method produces substantially faster computing times than the explicit FEM technique. AEM's properties make it excellent for modeling infilled masonry walls (Helmy et al, 2015; Zerin, 2017). This technology was used in the commercial program, Extreme Loading System. Building simulation models for explosives and earthquakes have been created. The program for progressive collapse simulation comprises slab collapse-failure modes, building demolition case studies, simulation of a macro crack pattern at failure, and bucking simulation applied to rubber material (Meguro and Tagel-Din, 1999). Non-linear buckling and massive displacement analysis Because of the commercial nature of this application, it is difficult to watch the progress in this direction. The validation, however, is limited to a single bridge beam case, and the response curve indicates an unexpected ultimate strength limit that the method's nature must comprehend. The absence of extensive validations can be recognized when the software claims to be fit for purpose in the safety evaluation of progressive collapse in structures. Even though the finite component approach is a well-established and accepted structural analysis tool, it is not suited for progressive collapse analysis. The finite element approach to gradual collapse analysis has significant drawbacks (Salem et al., 2011). Component damage, segregation, dropping, and collisions with additional components are all highly difficult. The GSA and UFC standards were designed to approximate and simplify the gradual collapse analysis so that it could be easily performed using the finite element method. Nonetheless, the approach proved to be so challenging that it needed many analytical tries (Hartmann et al, 2008). Because the calculations required to model real-world building collapses using traditional FEM are too expensive, a multibody model-based technique was used. The finite element method has been utilized by researchers to study the slow collapse of frame structures (Agnew and Marjanishvili, 2006; Yao et al, 2009). Figure 9 depicts a model created by Kaewkulchai and Williamson (2003) for a gradual collapse analysis of frames. Forces equivalent to and opposite to the failure column's component forces are applied to the node associated with the collapsed column to reflect the first deformations before column removal. The uniform load w, as well as the applied forces P, V, and M, are slowly applied to the frame in this example to produce static deformations. When all loads have been maximized, applied forces axial, shear, and moment are withdrawn to mimic a starting breakdown scenario. The approach, nevertheless, isn't the action of a catastrophic collapse (Kaewkulchai and Williamson, 2003).

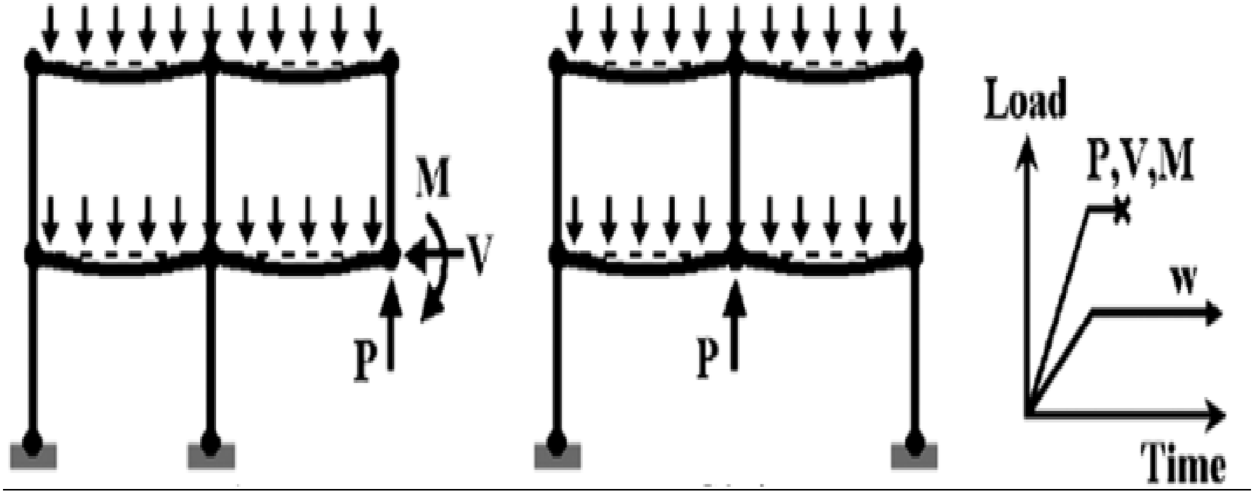

Figure 9: Analysis of the gradual breakdown by (Kaewkulchai and Williamson, 2003).

has been carried out by (Salem et al, 2011) to design five-floor RC buildings with a total height of 15 meters against progressive collapse using the applied element method for reinforcing bars and concrete, the system completely incorporates path-dependent nonlinear constitutive models. The model has had one or two center columns at ground level accidentally removed. Based on the findings of the analysis, In comparison to the FEM, the applied element method (AEM) is a more efficient, accurate, and simple approach for analyzing a gradual collapse. The collapse area may be computed in a single study by accounting for material nonlinearity, major deformations, and failure of parts, including division, and collisions across diverse structural sections are all possible. The Applied Element Method can be employed efficiently as an analytical tool to develop cost-effective designs for reinforced concrete structures that are resistant to progressive collapse. Using the applied element method instead of the finite element method resulted in a 50% decrease in the amount of redundant reinforcement in the examined situation. As seen in Figure 10, A system of normal and shear springs links the components along their surfaces. Normal and shear springs located at contact locations distributed on the element faces are designed to connect each neighboring component. Normal and shear springs are in charge of transmitting normal and shear loads. As seen in Figure 10, springs represent the stresses and deformations of a certain volume.

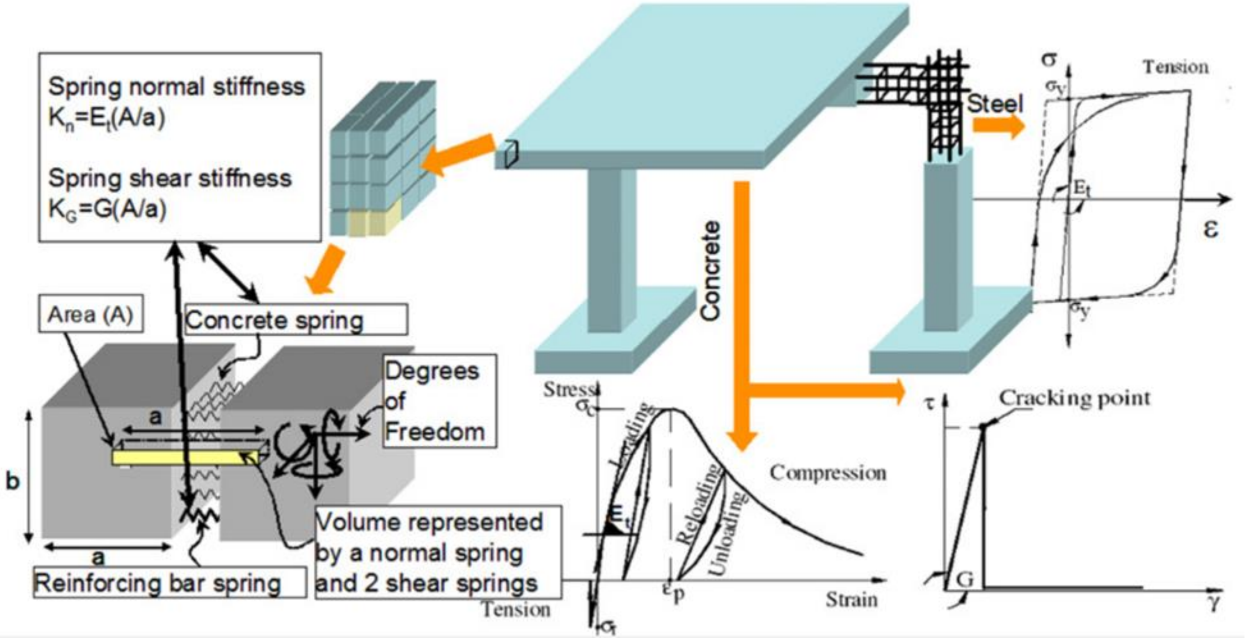

Figure 10: Modeling of a structure with the AEM (Salem et al, 2011).

The AEM employs fully nonlinear path-dependent constitutive models, as demonstrated in Figure 10. An elastoplastic and fracture model is used for concrete under compression (Maekawa and Okamura, 1983). When tension is applied to concrete, linear stress-strain equations are utilized until the concrete springs break, at which time the stresses become zero. Because the technique uses a discrete fracture approach, the reinforcing bars for the envelope are represented as bare bars, while the model (Ristic, 1986) for the inner loops, is used. The AEM is a stiffness-based approach that establishes an overall stiffness matrix and equilibrium equations, for structural deformations (displacements and rotations) are nonlinearly solved using each of the stiffness, mass, and damping matrices. The implicit solution for equilibrium equations is a dynamic step-by-step integration (Newmark-beta time integration) (Bathe, 1996; Chandler, 1997). The automated detection of element separation and contact is one of the AEM's most significant characteristics. If the matrix springs that link two near components fail, the components might separate. Components can divide, reconnect, or make contact with other components on their own.

C. Discrete Element Method

Other scholars refer to it as the independent element method (Cundall et al, 1979). With this technique, the finite element method was employed to simulate the behavior of a structure in high-loading situations. Structures are frequently split into several stiff bodies connected by springs. DEM computation takes time, especially for big models. (Lu, 2009) recently used DEM to examine progressive collapse, and (Masoero et al, 2012) were likely the first to focus on the progressive collapse of framed buildings. Some academics are working to increase efficiency and decrease processing time. Several studies employed combined FEM and DEM to increase efficiency and decrease processing time (Munjiza et al, 2004). A discrete element model (DEM) was proposed by (Lu et al, 2018) for the collapse analysis of reinforced concrete (RC) frame buildings using a modified segment-multi-spring model (SMSM). The program was applied to a real building damaged by the Wenchuan earthquake, and the results matched an in-person seismic damage assessment. The simulated results support the experimental findings. The conclusion arrived at was The following characteristics distinguish the proposed DEM-based numerical collapse modeling: The inclusion of a new element for contact sensing is one alteration. All of the components are divided into failed and effective groups, and component contact is then confined to detecting contact at component corner points, which may significantly reduce the computing burden and avoid difficult mathematical methods. Another advantage is that the discrete element's angular displacement in the global coordinate system is always available. Finally, spring failure criteria have considered coupling effects and may effectively account for the loss in shear stiffness of concrete axial springs after crush as well as the influence of reinforcement springs when the shear spring fails.

IV. CONCLUSION

FEM is the most developed and well-established method for solving nonlinear problems. However, due to the above objectives, it faces difficulties involving the requirement for material discontinuity simulation arising from progressive cracking or softening, fracture or crush of pressurized concrete, and tension bar rupture. The significant distortion of the collapse problem adds new obstacles to FEM models. The stiffness matrix, for example, will be asymmetric, needing more iterations in the solution. Because overall harm to objects is fleeting, synthetic methods are necessary to balance the removal pressures caused by deleted items. and simulation utilizing FEM based on simplified (macro) models; these models benefit from the problem's minimal number of unknowns. The models described in the literature, on the other hand, are validated only after the arching point. As a result, although it may be an acceptable approximation for the ultimate strength stages 'I and II', it is not the best for the collapse progression analysis as mentioned in phases 'III and IV'. The provided simulations are just correct for the mechanism's elastic response and do not provide full validation of goal 1. Although the FEM is a trusted and widely recognized building evaluation method, it is not ideal for progressive collapse analysis. This article examined the numerical analytical methods utilized in the study of the progressive collapse of the RC frame's structure in depth. Mapping simulation surveys to particular simulation aims, as well as repackaging and summarizing the preceding comments:

1. Extremely high-resolution simulations have major convergence issues, making it hard to examine the problem at the level of the building or when several components of the process are being investigated. Such an issue is exacerbated when the precise description of multiple interacting material responses, such as those outlined in phases II and III of the response curves, is not adequately portrayed. When the simulation model's structures are properly described, adaptive step-size and line-search algorithms can be employed to speed convergence. The falling portion of the steel strength curve beyond the point of ultimate strength, as well as the fracture stress-strain relationship, affects stirrups, shear crack opening, and locking (the third stage of the reaction).

2. Multi-platform models failed to describe the evolution of inelastic material reactions to another system component, particularly those depending on the slave-master stiffness matrix description.

3. Downstream simulations are limited to the model's detail reduction technique and cannot reflect the gradual changes in stiffness in the third stage, which is crucial for calculating the dynamic load increase factor for the required bond strength.

4. Even though the dynamic effects of the mechanism's moving mass have been accurately captured, None of the available models in the literature combine real-time and gravitational impacts into the simulation process, which is essential to duplicate the whole reaction route throughout the four separate stages. It was instead excluded as an additional processing step, and the validated simulations provided only provided checks in certain regions. When implicit simulation is not yet achievable, a wide spectrum of audiences have found explicit tactics appealing. The drawbacks are as follows:

1. Quick steps, thorough validation, and a focus on error progression Because of these general faults, the actual implementation It's hard and iterative, reliant on experience and judgment. which emphasizes the risk of human mistake and poor implementation.
2. In terms of elaboration effort, the simple model in this class is the most dangerous, but once the collapse of masculinity is specified, it provides a great tool for deterministic analysis. In other words, it is an effective technique for goals 2 and 3. In target 1, however, it is erroneous because multi-level plastic deformation exists and force redistribution is critical. Almost all scientific studies have been simplified in some fashion. However, such models may take some time to analyze.

A summary of the findings should be included in the conclusion. It should clearly express the contributions, the importance of the findings, and, if applicable, suggestions. It is often spoken in the past tense.

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