Use of layout optimization to identify optimal bracing systems in buildings

Many studies of the efficiency of lateral stability systems for buildings have been undertaken over the years. However, current design procedures appear not to be underpinned by clear fundamental principles. In this study, arrangements of bracing members are sought using the well-known layout optimization technique. The efficacy of the techniques is demonstrated by using it to identify the optimal arrangement of bracing and column elements in a small-scale building. When member buckling effects were ignored, the stiffness to material usage ratio of a braced bay was found to be 32% greater than when traditional diagonal cross-bracing was used – or 19% greater when buckling effects were accounted for.

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I. Introduction

The bracing system is an indispensable part of any building. This is particularly important in a tall building structure where the requirements for lateral stiffness may govern the layout of the whole building. Consequently, the design of the layout of the bracing required to resist lateral wind loading is an active area of structural engineering research. Studies of the optimality of bracing systems has typically involved the use of a given, fixed, topology, and then used either geometry or size optimization to identify the best solution. For example, Moon (2007) analysed diagrid bracing systems, using the angles between bracing members as parameters which were varied to optimize the lateral stiffness of the structure. Baker (1990) presented a bracing size optimization technique based on energy methods. Others have used continuum optimization techniques (Stromberg 2012; Liang 2000) or evolutionary optimization approaches (Richardson 2013). What has rarely been considered is the use of efficient, classical discrete layout optimization methods to identify benchmarks against which the performance of different design solutions can be judged.

The mathematical basis for the problem of finding the structural layout consuming least material was developed by Michell (1904). Whilst the analytical approach put forward by Michell provides a strong foundation for the structural optimization field, it is rarely helpful in a specific structural design application, because of the difficulty in finding an optimum structure for a given set of loading conditions. However, Michell's approach readily lends itself to numerical implementation, where the optimal layouts of discrete bar members are found from a "ground structure" comprising all possible interconnections between discrete node points within a design space. Using linear programming (LP) techniques numerical results can be found which provide close approximations of ideal Michell forms for a given problem (Dorn 1964; Hemp 1973). However, despite the efficiency of LP, even this method become computationally intractable for large-scale problems, due the number of potential members in the ground structure. Consequently, an improved, iterative "member adding" method was developed by two of the present authors, which dramatically decreases the computational cost, allowing very large scale numerical problems to be addressed (Gilbert and Tyas 2003). In this study, this approach is used to investigate optimal bracing layouts for different scenarios.

Previous workers have often considered the optimization of bracing systems where a beam and column framing system has already been designed to carry gravity loads, and where the load cases considered for bracing design involve only lateral loads. Stromberg et al. (2012) considered the effect of the stiffness of the columns on the optimal bracing layout, considering a single structural bay aspect ratio in their study. Liang et al. (2000) considered several bay aspect ratios, and found that the column and beam sizes determined from the gravity load analysis were adequate for the lateral load cases and geometries investigated. This raises two questions: (i) if the columns and beams designed for gravity loads can be assumed to have sufficient reserves of strength to act as part of the lateral stability system, can we find general rules governing the layout of the latter?; (ii) what are the optimal bracing layouts for frames where the structural layout is optimized for both gravity and lateral load cases, and combinations thereof. Both these questions are addressed in the present study, though here the focus is on (ii).

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II. Optimal bracing layout for small-scale building

A design example involving a typical naturally ventilated office considered by Brettle and Brown (2009) is here used to demonstrate the potential for layout optimization to be applied to building framing system design. The layouts of columns and bracing members are first optimized using plastic methods, using British Standard load cases (i.e. both vertical and lateral loads are considered). Bracing and column members are then resized if necessary to ensure buckling failure does not occur. The section details of both a traditionally designed and optimized braced bay are shown in Figure 1. It is worth noting that, during the optimization process, beams are treated as pre-existing members with infinite strength since they are always designed only according to gravity loading.

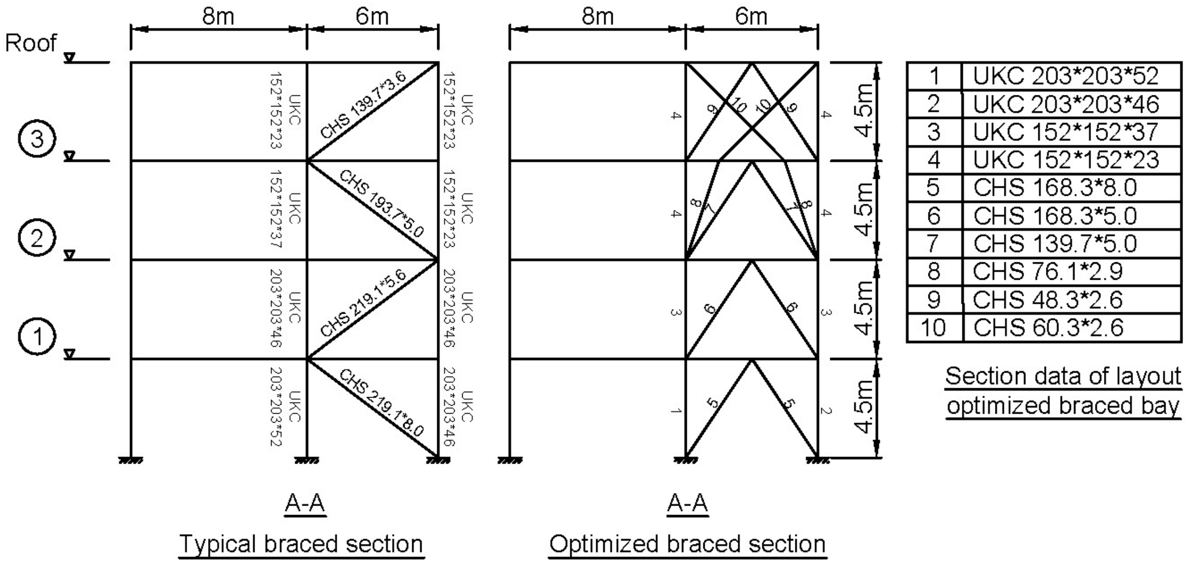

Figure 1 Optimization of a braced bay in a small-scale multi-storey building

The two braced bay can be compared in terms of both total material usage and lateral stiffness. It was observed that the stiffness to material cost ratio was 32% greater when layout optimization was employed, initially ignoring buckling considerations. When buckling considerations were included the volume of material required increased and the stiffness to material cost ratio was 19% greater when layout optimization was employed. Second order effects can be checked using the parameter α_{cr} defined in Eurocode 3. With the sections shown in Figure 1, each α_{cr} of floors in the optimized braced bay is larger than the threshold value defined by the Eurocode (i.e. 10), which means second order effects can be neglected.

III. Conclusions

Layout optimization appears to provide a useful means of identifying optimal bracing systems in buildings. Future work will focus on extending the layout optimization technique so that rigid-jointed framing elements can also be modelled.

IV. References

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