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An investigation of the effects of socket joint flexibility in space structures

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ABSTRACT

Connection of truss elements using socket joints is one of the more common practices in the construction of space structures. Although these hollow spherical joints may deform due to the applied loads, these deformations and the resulting effects on the member axial forces are usually ignored in the analysis and design. This work is an investigation of the effects of socket joint deformability on the behavior of space grid structures. Here, the load–deformation relationships obtained from a series of biaxial loading tests on actual socket joints have been used to represent their behavior in several finite-element analysis models. These models have been analyzed using a special-purpose substructure finite element analysis program developed to account for full geometric and material nonlinear behavior. It has been demonstrated that in many occasions, node deformability results in significant changes in internal member forces, overall structural stiffness, and the limit load behavior of the structure.

1. Introduction

A rather considerable number of connection systems have been developed for use in skeletal space structures, including solid ball joint systems, socket joint systems, plate joint systems, slot joint systems, and shell joint systems [1] among others. The importance of node and jointing system on the overall behavior of skeletal space structures is so vital that many commercial space structural systems are identified mainly by their jointing details. The socket joint system studied herein has been developed by Akam Felez Co. Ltd. as discussed in Ref. [1]. The jointing system consists of hollow steel spheres that are fabricated by two-stage forging of circular plates, providing access for bolting the joints into the internally threaded end cones of the connecting members. A typical joint studied herein is shown in Fig. 1 [2].

The characteristics of jointing systems and their influences on the structural behavior of space trusses have been studied by several researchers as well as manufacturing companies. To this end, the behavior of many of such joint systems subject to forces applied from connecting elements has been well examined and understood. For example, experimental studies on MERO joints developed by Max-Mengeringhausen have been carried out not only by the MERO Company, the original fabricator of the system [3], but also by other researchers. Among others, Chenaghlou [4] have studied the effects of bending rigidity of MERO joints when subjected to various loading conditions. Also in connection with the influence of bolt tightening on the structural behavior of double layer grids of the MERO jointing system, one may refer to the work of Davoodi et al. [5] and Gholampour et al. [6], who tested a part of a double layer grid, and also Gholampour and Maalek [7], who conducted experiments on more than 40 pyramidal modules of MERO-type solid ball joints with different degrees of bolt tightness and demonstrated the dependence of the effective lengths (and thus the slenderness ratios) of members upon the degree of bolt tightness. More recently, Ma et al. [8] analyzed several finite element models to obtain moment–rotation relationships for socket joints subjected to uniaxial compression. It is to be noted that most of researches that have reported on the joint flexibility, corresponding to solid ball joints of space trusses, are mainly concerned with the degree of moment transfer at joints and/or eccentricity resulting from imperfections introduced during fabrication and erection. So is the majority of the literature on the analysis of space frames with semi-rigid joints [9]. In a socket joint, however, the deformation of the joint itself can be significant, and may affect the axial loads of the connected members. In addition to the properties of the joint itself, the amount of joint deformations depend on loading conditions and the stiffness of connected members. Through an experimental study, Maalek [2] showed that the axial deformations of the socket joints designed and manufactured for use in an aircraft hangar were considerable at limit loads in such amounts that affected the behavior of the entire structure. In another study, Maalek and Faam [10] inserted the experimental results of socket joint deformations in a computer program to analyze relatively simple grid structures accounting for the influence of deformations of socket joints themselves in addition to the member instability based on a pre-assumed buckling behavior.

In this paper, the effects of socket joint flexibility on the overall behavior of actual-size space structures are studied. For this purpose, a special finite element analysis program is developed that can take any form of joint deformation behavior into account. Following the

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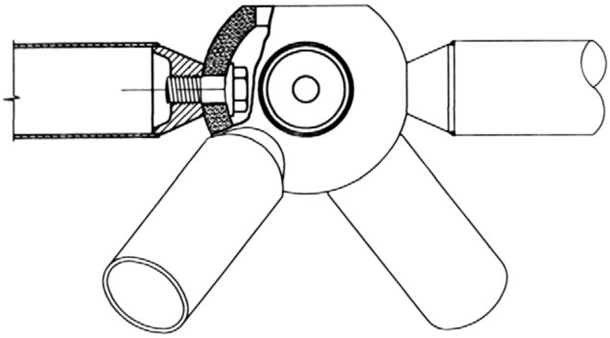

Fig. 1. Akam Felez socket joint system [1].

introduction of this analysis program, the behavior of several analysis models have been studied in two cases: i) considering joint deformations and ii) ignoring joint deformations. In order to realistically demonstrate the importance of the joint deformations addressed above, the experimental results of tests on socket joints of an actual structure (Homa Aircraft Hangar No. 3 [2]) has been incorporated in the analysis of the representative structures investigated herein. These tests have been carried out in accordance with the requirements of Chapter 7 of the Iranian Code of Practice on Skeletal Space Structures [11]. The first series of analyses have been carried out on a few structural configurations, considered as benchmarks, to investigate the effects of the socket joint deformations on their behavior. Finally, as a practical case study, an actual space structure designed and constructed with socket joints has been investigated.

2. The behavior of socket joints

It has been observed in experimental studies [2] that the measured deformations of the tested specimens for the joints made of ST37 steel became excessive at the loads about 1.5 times the allowable capacity of a number of connecting members of the corresponding structure. Fig. 2 shows a typical deformed shape of a socket joint specimen subjected to biaxial loading. These deformations are sometimes accompanied with bearing deformations of socket joints at bolt heads or member ends. It should be noted that mainly due to the significant amounts of residual stresses that develop by the forming procedure used for the construction of these joints, finite element analyses of joints do not usually lead to matching force–displacement behaviors. The biaxial test results can be averaged and represented – with sufficient accuracy for design purposes – by a series of simplified bilinear idealization of load–deformation graphs for different loading conditions as shown in Fig. 3. In this figure, F_1 and F_2 represent the applied load components in two perpendicular directions, F_1 being the major component. The parameter r is then defined as the ratio of the magnitude of the smaller force to that of the greater force, namely F_2/F_1. Each graph in Fig. 3 corresponds to the bilinear idealization of the actual relationship between F_1 and the joint deformation, Δ, for a certain range of the values of the ratio, r. The joint deformation is defined as the elongation or compression of joint diameter measured in the direction of the major force component, F_1. Such representation helps easily create a database of experimental results, each entry of which contains the loading directions and ratios, initial stiffness, yield force and post-yield stiffness. It can be seen from Fig. 3 that:

i) In the case of biaxial compression (Fig. 3-a) or tension (Fig. 3-b), as r increases, both the elastic limit (assumed to coincide with the proportionality limit of socket joints) and the slope of the post-elastic part of the graph also increase. However, for a selected range of the values of r, the elastic limit load is considerably larger in the case of biaxial compression than in biaxial tension.

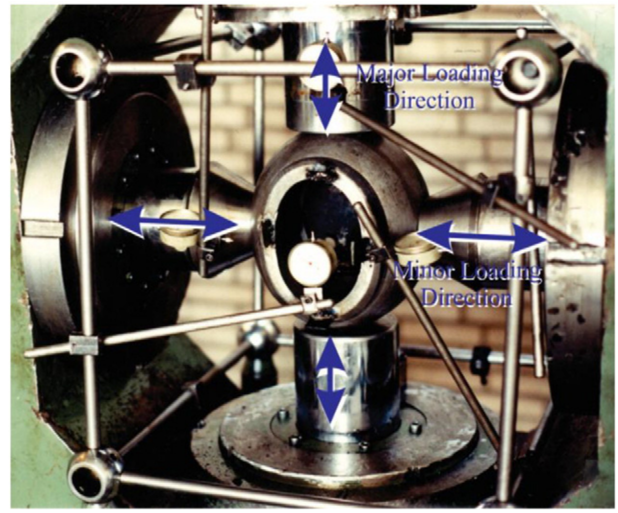

Fig. 2. Deformation of a socket joint in a biaxial loading experiment by Maalek [2]. This setup applies biaxial compression; horizontal component being the major force.

ii) Referring to Fig. 3-c and d, under various combinations of compressive and tensile loading, the elastic limit and the slope of the post-elastic part of the graph increase as r decreases. Considering any range of the values of the quantity r, here the magnitude of the biaxial system of loads corresponding to the elastic limit is larger when F_1 is compressive.

It can be seen that the post-elastic joint deformation becomes considerable, particularly in the case of biaxial loading with deviatoric load conditions (i.e. combinations of compressive and tensile forces acting along two perpendicular axes). This is more pronounced when r approaches unity even for rather small values of biaxial forces.

Depending on the loading conditions and the structural configuration, the joint deformations will naturally lead to a redistribution of member forces in an actual structure. From this standpoint, two force redistribution scenarios may be considered: (i) in near uniaxial or symmetric loading conditions on a joint, the restraints provided by adjacent elements attached to that joint would prevent free joint deformations at the expense of additional loads to be imposed on those elements, and (ii) in anti-symmetric loading conditions, the forces along perpendicular axes tend to increase the joint deformations much beyond those of uniaxial loading, affecting the internal forces of the connected elements.

In a three-dimensional space truss, joints are generally under the action of triaxial loading. However, a series of elastic analyses of the triple layer grid discussed in [2] (and investigated as a case study here) showed that except for a few joints near supports, most of the critical joints were mainly under the action of either almost uniaxial forces (with negligible forces acting in other directions), or biaxial forces (with negligible forces acting in the direction perpendicular to the planes of biaxial loading). This is expected to be also the case for many large span flat grids that are simply supported along their perimeter. By recognizing the major plane of loading – in which the major biaxial force resultants lie – the biaxial test results can be used to approximate the joint behavior and estimate the joint deformations in that plane. These deformations can then be used in order to predict the overall structural behavior. Although the use of bi-axial test data is expected to result in some loss of precision, the accuracy of results are considered to be adequate for design purposes, since it is only detrimental where joints are subjected to strong forces along three orthogonal axes. In the latter case, it may be necessary to carry out triaxial tests based on which similar procedures for the derivation of joint behavior can be followed. The resulting relationships can then be fed into the analysis