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DETERMINATION OF INTERNAL FORCES IN END PLATES OF SIMPLE END PLATE JOINTS

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Key words: end plate joints, internal forces, end plate.

Abstract

In the paper the authors propose computer simulation of simple end plate joints. A computer model has been elaborated using the Autodesk Robot Structural Analysis Professional 2010 software programme. Maps of internal forces and stresses on end plates of a joint have been analysed. The analysis of the maps enabled the authors to determine the course of variation of bending moments in any cross-section of the joint and to compare the obtained diagram with a diagram of moments cited in the literature (ŻÓŁTOWSKI et al. 2000, BIEGUS 1997), which serves the purpose of determination of the minimum thickness of end plates needed due to the lever effect. The paper also determines the dependence between the loading force acting on the joint and the thickness of end plates on the assumption of maximum stresses damaging the steel of the end plates, as this is one of the criteria for dimensioning end plate joints. In addition, effort of joint bolts was determined in relation to a value of the loading force.

WYZNACZENIE WARTOŚCI SIŁ WEWNĘTRZNYCH W BLACHACH CZOŁOWYCH POŁĄCZEŃ DOCZOŁOWYCH ZWYKŁYCH

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Słowa kluczowe: połączenie doczołowe, siły wewnętrzne, blacha czołowa.

Abstrakt

W pracy zaproponowano symulację komputerową połączenia doczołowego zwykłego. Model komputerowy opracowano na podstawie programu Autodesk Robot Structural Analysis Professional 2010. Przeanalizowano mapy sił wewnętrznych i naprężeń na blachach czołowych połączenia. Analiza map pozwoliła określić przebieg zmienności momentów zginających w dowolnym przekroju

połączenia oraz porównać uzyskany wykres momentów z wykresem momentów podanym w literaturze (Żółtowski i in. 2000, Biegus 1997), służącym do określenia minimalnej grubości blach czołowych ze względu na efekt dźwigni. W pracy określono również zależność siły obciążającej połączenie od grubości blach czołowych, z założeniem maksymalnych naprężeń niszczących stal blach czołowych. Jest to jedno z kryteriów wymiarowania połączeń doczołowych.

We wzorcowym połączeniu wyznaczono również wytężenie śrub połączenia w zależności od wartości siły obciążającej.

Introduction

In contemporary steel constructions, bolt joints are mainly used for joining shipping or assemblage elements. End plate joints, either non-bolted or bolted with high strength bolts, are a modern way of joining stretched or bent elements of metal constructions, in which the main component of the load is parallel to the axis of the bolts. These joints can be made easily and quickly at a construction site under any atmospheric conditions and without any heavy or specialist equipment. With such joints, it is also possible to assemble and, if necessary, dismantle a steel construction easily.

This paper discusses the problem of the effort of bolts and end plates in simple, strechted end plate joints. Among the most important issues which have not been solved satisfactorily until present day are distribution of internal forces in a joint (in end plates and in bolts), the way the edges of end plates interact with one another, the lever effect on the actual bearing capacity of a joint and the minimum thickness of end plates. Moreover, the nature of the work performed by bolts and the effect of the thickness of end plates on the character of work performed on end plates in end plate joints still await complete clarification.

Description of a computer model

In order to improve our understanding of the above problems, a computer-based simulation of a simple end plate joint subject to stretching has been completed using the software programme called Autodesk Robot Structural Analysis Professional 2010 licence 3251. A stretched end plate joint was designed in the form of two plate girder double-tee bars joined through end plates with M16 bolts fixed in ϕ 18 holes (Fig. 1).

The connection of the end plates was modelled as a joint of plates restrained at the sites where bolts joining the plates were fitted. The end plate joint was made using a fixed connection with a ϕ 16 rod, which simulated the properties of a grade 8.8 M16 bolt with all degrees of freedom being blocked (Fig. 2).

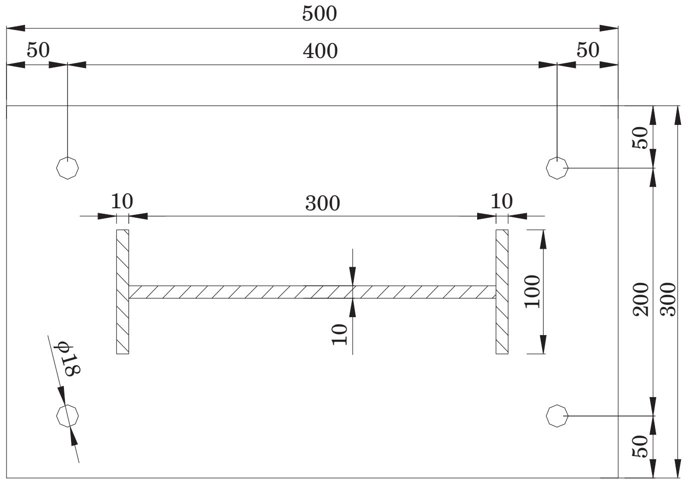

Fig. 1. A model of an end plate in a joint. Thickness of the end plates in the end plate joint is g_b = 16 mm. Thickness of the plates of the connected rods is g_p = 10 mm
Source: own elaboration.

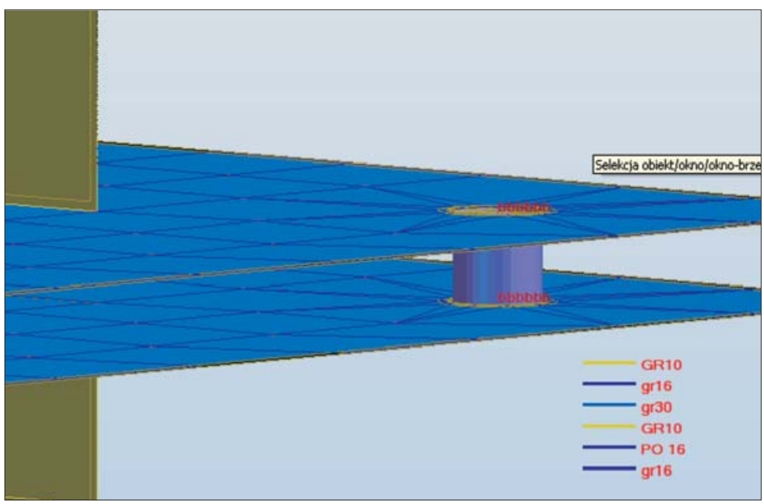

Fig. 2. Model of the bolted joint of end plates: rod ϕ 16. Steel in the bolt simulating grade 8.8 steel.
Source: Autodesk Structural Analysis Professional 2010 licence 3251.

It was assumed that the end plates and connected rods were made of S235 grade steel. The bolts were modelled from steel of mechanical properties close to those of grade 8.8 bolt steel. The bottom part of the joint was supported by articulated line supports. To the upper one, the connected plate girder rod, concentrated transmitted load was applied. The load was applied to the middle node of a FEM grid at the upper edge of the plate girder web. A Finite Element Method grid was established according to Coonse's method, allowing for adjustment of FEM grids. Around the joints there were visible codes of blocked degrees of freedom.

In the subsequent stage of the simulation, thicknesses of end plates were changed, thus determining the dependences between the force causing normal damaging stresses and the thicknes of the end plates. In addition, the value of the load on the joint was determined at which the efforts of the bolt steel were close to one.

Analysis of the results

The following were obtained: a map of normal stresses on the upper surfaces of end plates (Fig. 3), a map of bending moments M_y (Fig. 4) and a map of translocations of the FEM grid centres (Fig. 5).

At the same time, in the vicinity of the effect produced by the bolts, a diagram of variation of bending moments was made, which verified diagrams of bending moments accepted in the literature (ŻÓŁTOWSKI et al. 2000) (cross-section A–A) (Fig. 6). Żółtowski presents a diagram of bending moments at the contact edge of end plates assuming a zero value of bending moments at the longitudinal edges of the end plates (Fig. 7).

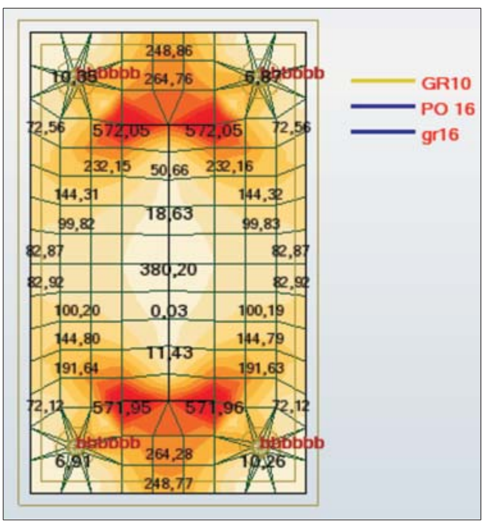

Fig. 3. Map of normal stresses in upper fibers of end plates in the joint
Source: Autodesk Structural Analysis Professional 2010 licence 3251.

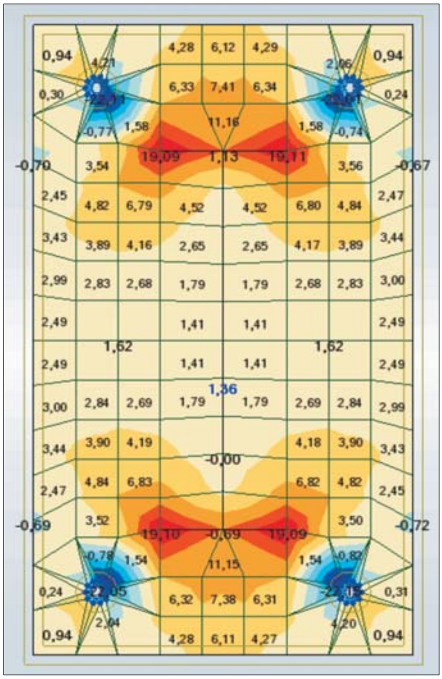

Fig. 4. Map of bending moments in upper fibers of end plates in the joint
Source: Autodesk Structural Analysis Professional 2010 licence 3251.

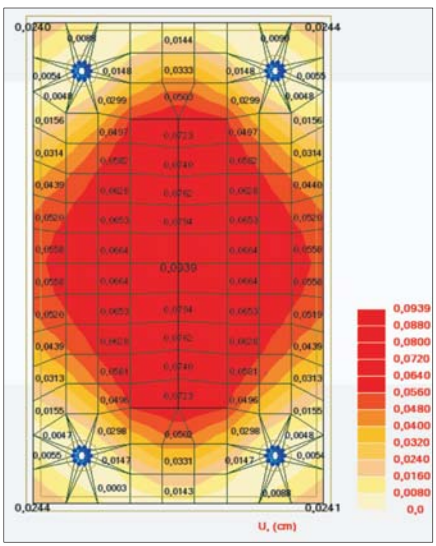

Fig. 5. Map of translocations of the FEM grid nodes in end plates of the joint
Source: Autodesk Structural Analysis Professional 2010 licence 3251.

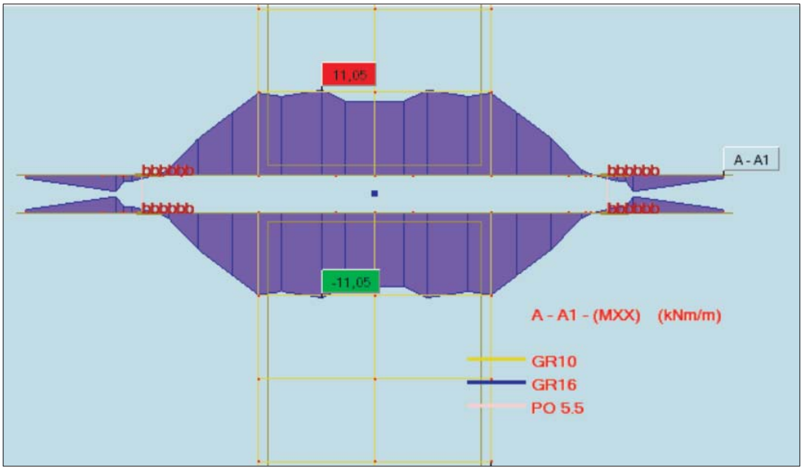

Fig. 6. Diagrams of bending moments M on end plates of the joint
Source: Autodesk Structural Analysis Professional 2010 licence 3251.

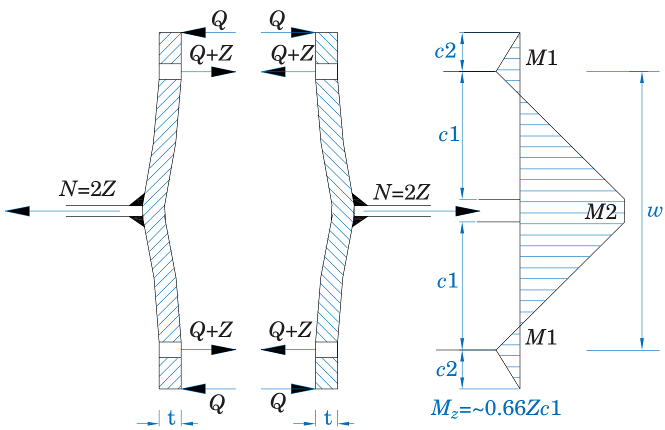

Fig. 7. The lever effect and diagram of moments on the surface of an end plate in an end plate joint
Source: own elaboration.

Taking advantage of such a diagram of moments, he derives a known standard dependence for the minimum thickness of end plates. It assumes that moment $M_z = \sim 0.66\, Z \cdot c_1$ (Fig. 8, 9). By distinguishing mentally a strip of the endplate of the width b_s (Fig. 10), one can determine the value of moment M_z (DOMINIKOWSKI et al. 2005).

$$M = 0.66 \cdot c \cdot Z = W \cdot f_d \Rightarrow \frac{M}{W} \leq f_d \tag{1}$$

$$W = \frac{1}{6} \cdot b_z \cdot t^2 \tag{2}$$

$$0.66c \cdot Z = 0.167 \cdot b_z \cdot t^2 \cdot f_d \tag{3}$$

$$t = \sqrt{\frac{0.66 \cdot c \cdot S_{Rt}}{0.167 \cdot b_z \cdot f_d}} = \sqrt{\frac{c \cdot S_{Rt}}{b_z \cdot f_d}} \tag{4}$$

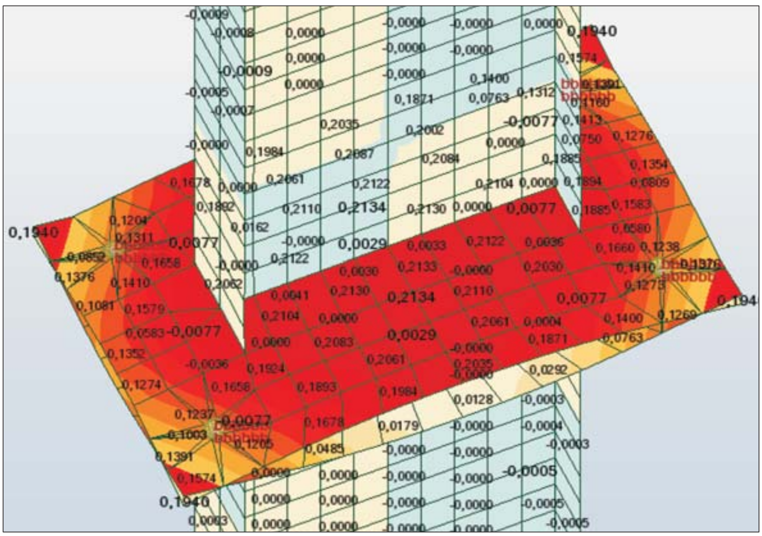

Fig. 8. Deformation of end plates in the joint
Source: Autodesk Structural Analysis Professional 2010 licence 3251.

Due to the limited increase in the value of the force in a bolt caused by the lever effect, it is assumed that the minimum thickness of the plate in the joint is $t_{\min} = 0.6$ t.

Then, the minimum thickness of the plate is:

$$t_{\min} = 0.6 \text{ t} = 1.2 \sqrt{\frac{c \cdot S_{Rt}}{b_z \cdot f_d}} \tag{5}$$

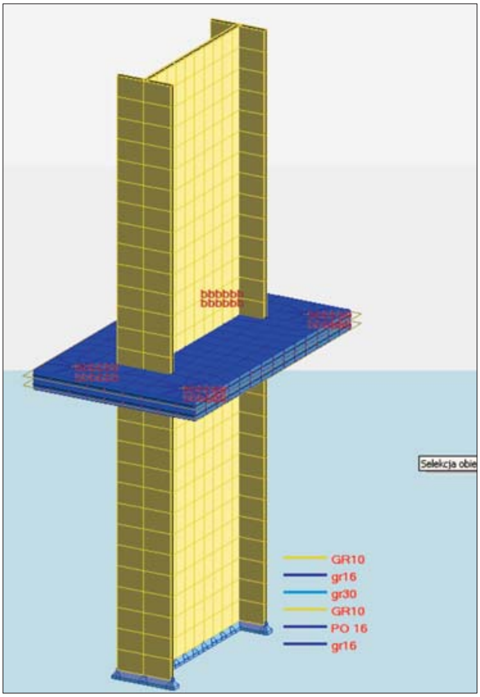

Fig. 9. Computer model of the analysed joint
Source: Autodesk Structural Analysis Professional 2010 licence 3251.

The above dependence is valid as long as the bending moment at the edges of the end plates is assumed as zero (PN-90/B-03200). In reality, at the endplate edges are there are non-zero, residual bending moments and normal stresses (Fig. 3, 9). The assumption that bending moments at end plate edges are equal zero is quite a good approximation in the light of the analysis of the diagram of moments (Fig. 3, 9). The diagram of moments (Fig. 7) is close to the diagram of moments (Fig. 6), but the assumed values M_2 are higher than the actual ones (Fig. 6). The flattening of the diagram (Fig. 6) is caused by the stiffening of the plate along the x–x axis. Paradoxically, the presence of factor bz in the denominator of the fraction (Fig. 10) should diminish the thickness of endplates as the spacing of bolts in the joint increases (PN-90/B-03200).

The cases described in (ŻÓŁTOWSKI et al. 2000, BIEGUS 1997, MAREK et al. 2003) are applicable to relatively thin end plates stiffened along one direction. The computer-based simulation presented in this paper accounts for the bracing of end plates along both directions. The y–y axis is braced with the webs of the connecting rods, whereas the x–x direction is braced with shelves of connected rods.

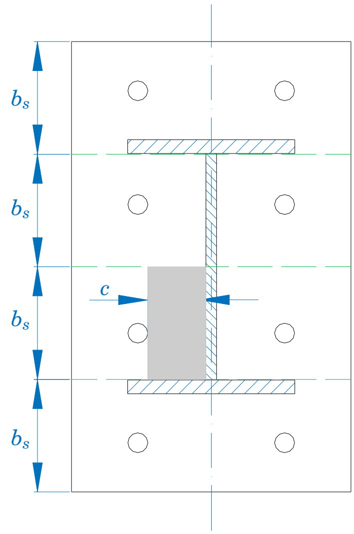

Fig. 10. Width of interaction of plate b_s per one bolt and distance c from the edge of the hole to the outer edge of the weld
Source: own elaboration.

MAREK et al. (2003) describes a computer-based simulation of a joint based on the SBRA (Simulation-Based Reliability Assessment) method, assuming that supports at bolts are elastic and articulated at edges (the edge of one end plate is supported on the edge of the other plate). Both methods attain zero moments at edges of end plates and assume that plates have articulated supports. At the same time, Marek compares the SBRA results with the EC3 recommendations (prEN 1993-1-1:2002), repeated in later publications of eurocodes (PN-EN 1993-1-8:2006).

The results of the SBRA simulations are close to the results of the simulation reported in this paper and cited in (ŻÓŁTOWSKI et al. 2000, BIEGUS 1997). They are also approximately the same as the ones given in EC3. The formula for the minimum thickness of an end plate should also include non-zero valeus of moments at edges of end plates (Fig. 4).

Moreover the applied computer-based simulation allowed for determination of the dependence of the load on the joint on the thickness of the end plates in the joint, assuming that there appear normal stresses in the end plates which damage the joint. It was assumed that the steel in the end plates was S235 grade steel. For different thicknesses of the end plates, the joint was loaded with a force which caused the appearance in the end plate steel of normal stresses close to damaging ones. The assumed values of the axial force were such as to attain the value of extreme stresses in end plates close to the values causing damage to their steel. For S235 steel, the value was f_d = 375 MPa (PN-90/B-03200). These dependences are illustrated in figure 10. With such dependences, it is possible to determine the value of loads damaging the end plates in a joint. For a given thickness of an end plate, one can read the value of a force at which the values of stresses in end plates are nearly R_m.

The computations were performed for the thickness of end plates between 10 and 24 mm. The regression curve represents foreseen results of thickness of end plates up to 30 mm. At the same time, the value of a force was measured at which the efforts of the steel in the bolts are close to 1. The force which causes the break of grade 8.8 M16 bolts in the modelled joint is P = 320 kN. The load per 1 bolt is P_1 = 80 kN ≅ S_{Rt} 81.3 kN (PN-90/B-03200). The load capacity of a bolt in a joint also depends on the thickness of plates (the lever effect) and is lower for less thick plates (e.g. for a plate 16 mm in thickness, the load capacity of bolts is ~ 55 kN).

Conclusions

The currently available computer methods applied to analysis of constructions enable us to analyse more precisely how joints, including semi-rigid ones, work. Analysis of maps of bending moments (Fig. 4) makes it possible to verify the accepted static models of work of end plates. The assumption of zero bending moments at edges of plates is close to the distribution of bending moments (vector of moments along axis *y*) obtained in a computer-based simulation. At the edges of end plates there are moments whose values can be neglected while analysing how a joint works. They are residual in nature.

In bolts which join end plates, apart from tensile forces, there are also bending moments (Fig. 4). Values of bending moments on joining bolts decrease as the thickness of end plates of the joints rise. Diagrams of bending moments in a cross-sections in the vicinity of bolts obtained in our computer simulation are very close to the diagrams of moments presented in articles (ŻÓŁTOWSKI et al. 2000, BIEGUS 1997, DOMINIKOWSKI et al. 2005, MAREK et al. 2003). Little changes in the character of the distribution of stresses and bending moments on end plates were observed when different types of support given to edges of plates were assumed.

For any load on a joint, the question of mutual support of edges of end plates seems to be negligible because under the influence of loads there appears a gap between the end plates, as a result of which there is no mutual support of their edges.

In the simulation discussed in this paper, the maximum value of normal stresses on surfaces of end plates was achieved in the vicinity of the joint connecting ends of shelves of plate girders joined (welded) with end plates. This confirms the principle of concentration of stresses in these places.

The computer-based simulation presented in this article enabled the authors to determine the dependence of the load on a joint on the thickness of end plates, assuming that there are normal stresses on end plates close to R_m (Fig. 11).

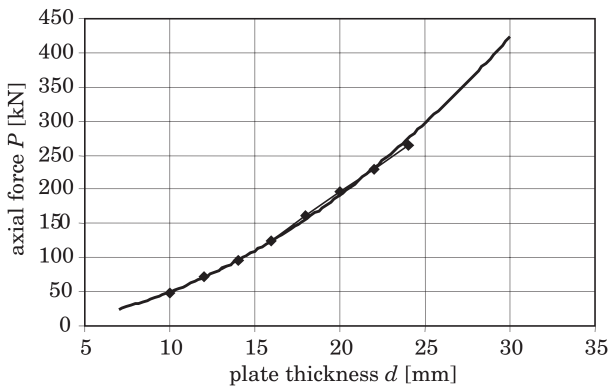

Fig. 11. Dependence of the axial force in the joint on the thickness of the end plates in the joint, on assumption of attaining stresses in the end plates that damage the joint
Source: own elaboration.

The simulation also made it possible to determine the values of forces which damage the joint by breaking the bolts. It turned out that on assumption that the joint would be braced with a rod modelled from steel whose mechanical properties were close to the steel from which the bolts were made, the obtained damaging forces were nearly identical to values S_{Rt} (PN-90/B-03200). At the same time, the authors observed a change in the value of axial forces P in the bolts depending on the thickness of the end plates. Therefore, the commonly accepted assumption about a reversely proportional dependence between thickness of end plates and the norm multiplier b_s (Fig. 10) seems questionable. Paradoxically, an increase in value *bz* diminished the minimum thickness of end plates.

The authors of this paper are fully aware of how fragmentary this analysis of semi-rigid joints is and are now working on expanding their analysis so as to cover more complex issues (greater density of bolts, analysis of welds) and on analysis of bent end plate joints.

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