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CRITICAL STRESS ASSESSMENT IN ANGLE TO GUSSET PLATE BOLTED CONNECTION BY SIMPLIFIED FEM MODELLING

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Abstract: *Simplified modelling of friction grip bolted connections of steel angle – to – gusset plate is presented. The paper considers: a) simplification of pre-tensioned bolt model, b) simplification of load transfer within connection. The simplifications influence on normal strain (and thus stress) distribution at critical cross-section is investigated. FE models were created using 1-dimensional and 2-dimensional elements. Angle flanges and gusset plate were modelled with 4-node shell elements of 6 degrees of freedom per node. Bolt holes were approximated by 16-side regular polygons. Two methods of modelling of friction grip bolting were considered: a) bolt-regarding approach ("bolted" model) – with 1D element systems modelling pre-tensioned bolts, b) bolt-disregarding approach ("tied" model) – with assumption that contacting element surfaces are tied over total area of contact of connected elements () or the area of ring around each bolt shank ("partially tied"). Modelling of friction grip bolted connections using simplified bolt modelling may be effective, especially in the case of analysis concerning elastic range. In such a case disregarding bolts and replacing them with "partially tied" modelling seems to be more attractive. It is less time-consuming and provides results of similar accuracy in comparison to analysis utilizing simplified bolt modelling.*

1 INTRODUCTION

Friction grip bolts are widely used in bridge engineering. They are applied in new structures as well as in old ones as rivet replacement (for instance during refurbishment or strengthening). This type of connection is specifically attractive in the case of structures sustaining periodically variable loading that is typical for bridges. Friction grip bolting generates stress concentrations much milder in comparison to welding.

Sophisticated numerical analysis of steel member connections is possible nowadays. Complex phenomena and processes are being taken into account by researchers [1, 2]. This is present especially when new structural solutions are tested, as part of pre-testing investigation or when databases of joints behaviour are created, usually aiming at aid in design practise.

Fig.1. Bridge truss girder bottom flange – to – deck transverse beam and wind bracing structural connection

However there are limitations to complex numerical modelling of joints, due to engineering applicability of analysis results. One of the limitations is the complexity of the joint itself. The good example is bridge deck transverse beam connection to bridge truss girder, the joint where bottom wind bracings may also be connected (see Fig.1). The geometry poses some difficulties as well as possible amount of bolts, even if only part of the joint is bolted. Such situation calls for simplified approach that would overcome software limitations as well as pre- and post-analysis work-time expenditure preserving results accuracy and providing engineering applicability.

The most common method of bolted connection simplification is simplified modelling of bolts themselves. Very often attention is drawn only to the main direction of load transfer. Transversely loaded bolts may be modelled [3] in completely different way than longitudinally loaded ones [4].

Furthermore, numerical analysis of friction grip connection may be carried out with an assumption that there is strain continuity over member contact surface with no slip. In this case modelling of bolts is unnecessary. This may require thorough investigation concerning choice of boundary of tied surface in the model since the actual boundary may be load level sensitive.

The paper deals with the simplification problems in terms of finite element method. The following are considered:

- simplification of pre-tensioned bolt model,
- simplification of load transfer within connection.

Paper investigates the simplifications influence on normal stress distribution at critical cross-section, that is crucial not only for computing load bearing capacity but fatigue strength as well.

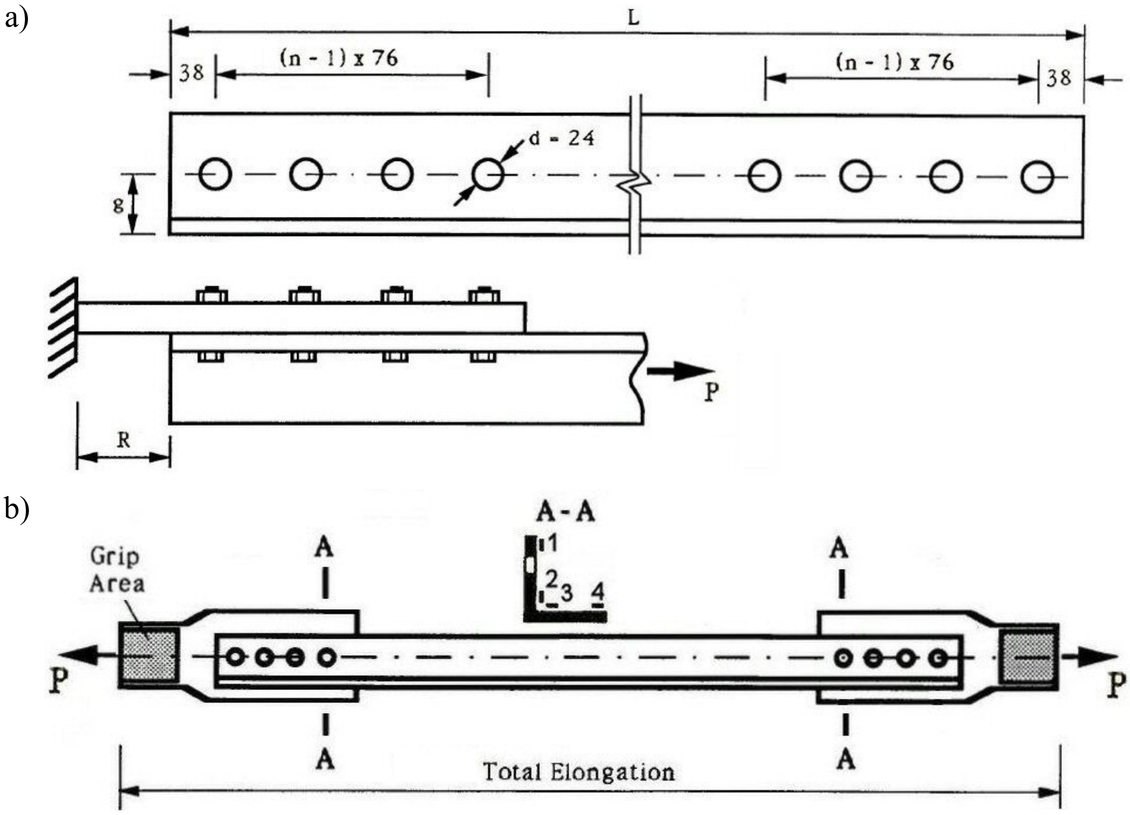

Fig.2. a) Bolts arrangement b) Location of strain gauges (*1*, *2*, *3*, *4*);
Base of *Total Elongation* measurement is explained

2 LABORATORY TESTING

Laboratory testing of angle to gusset plate connections was taken as basis for numerical analysis investigation. The testing is described in detail in [6]. Group of specimens, each consisted of an single-angle or double-angle member bolted to gusset plates, are considered there. The original aim of the testing was to establish the true load carrying capacity of such members. The general test data are given in Fig.2.

Tests of two specimens were chosen for numerical investigation: S1 and S11. For both of them the longitudinal strain distribution across the critical cross-section (A–A in Fig.2b) was recorded during testing as described in [6] – gauges 1, 2, 3 and 4.

Specimen geometry, physical and mechanical characteristics are given in Table 1 [6]. Gusset plate was 16 mm thick and 230 mm wide. M22 bolts were used for testing. Physical and mechanical characteristics of angle steel are given in Table 2 [6].

Table 1. Geometrical and physical and mechanical characteristics of analysed specimens [6]

Specimen symbol	S1	S11
Angle cross-section dimensions [mm]	$102^{*)}\times102\times6.4$	$76^{*)}\times51\times4.8$
Angle length L [mm]	2036	1992
Amount of bolts n	6	2
R (given in Fig.2a)	50.8	50.8
Modulus of elasticity [GPa]	200.14	204.85
Static yield strength [MPa]	340	339
Static ultimate strength [MPa]	524	487
Strain at ultimate [%]	17.7	17.6

$^{*)}$ flange bolted to gusset plate

Tested specimens were initially snug tightened to gusset plates, then 10% of predicted ultimate loading was applied. At this state nuts were rotated by 1/3 turn further [7] to satisfy the condition for turn-of-nut pre-tensioning. In this way the minimum pre-tensioning force generated was about 200 kN.

For un-treated surfaces steel-over-steel friction coefficient may be taken as μ=0.25. So one may assume that each bolt represented friction grip connected able to carry about 50 kN. Total load carrying capacity of connections due to friction is as follows: in the case of S1 (6 bolts) – 300 kN, in the case of S11 (2 bolts) – 100 kN.

The “snug-tightened” bolted connections utilise – in design – shear capacity of bolts as well. So slip prior to reaching static ultimate strength of connected member is allowable..

3 FINITE ELEMENT ANALYSIS

FE models were created using 1-dimensional and 2-dimensional elements. General view of models is given in Fig.3. One half of each specimen, up to lateral symmetry plane, was considered. Along the A-B and A-C edges (Fig.3) constraints present at symmetry plane were applied at nodes. Along the D-E edge of gusset plate (Fig.3) clamping was assumed, however the nodes at this edge were free to move in direction parallel to initial direction of angle. The displacement was used as numerical analyses driving factor.

Angle flanges and gusset plate were modelled with 4-node shell elements of 6 degrees of freedom per node. Bolt holes were approximated by 16-side regular polygons.

Physical and mechanical characteristics of angle steel were taken according to the Table 2. Bilinear approximation of constitutive law was assumed. Since there was no sign of gusset plate yielding during tests, the gusset plate steel was assumed to be ideally elastic in FEM models: steel elastic modulus E=205 GPa and Poisson’s ratio as ν=0.3. Similar approach was applied to beam elements of bolt model.

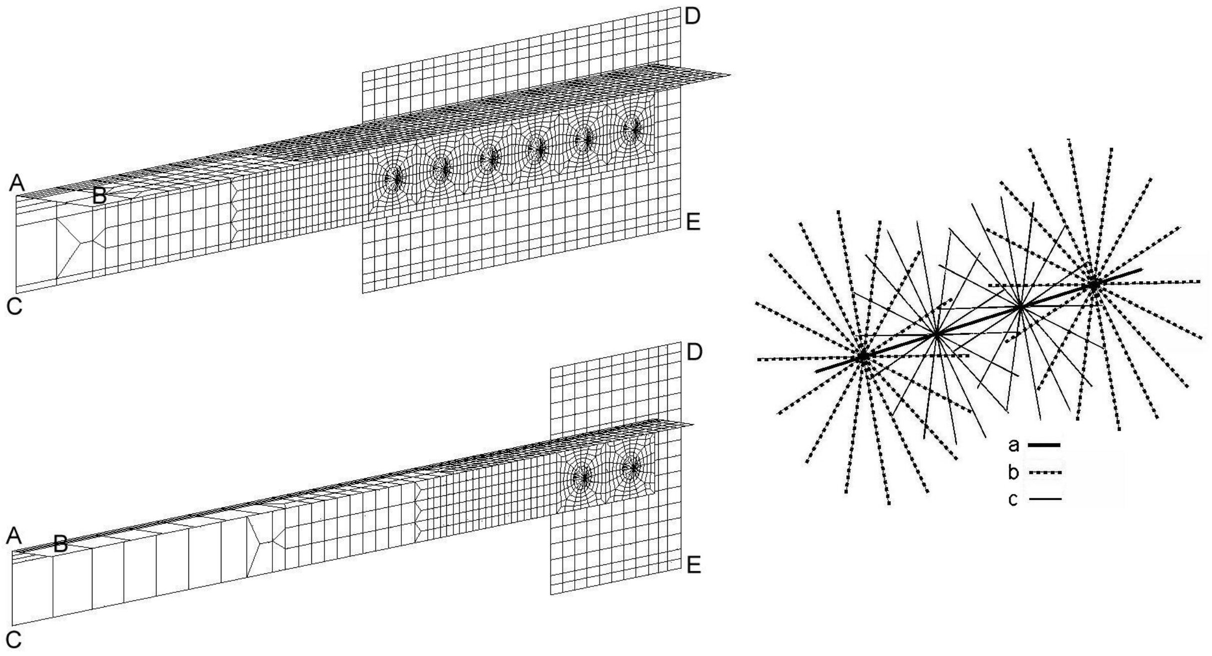

Fig.3. FEM models: specimen S1 (top, left), specimen S11 (bottom, left), bolt (right)

Two methods of friction grip bolted connection modelling were considered:

a) method 1.: bolt-regarding approach ("bolted" model) – with 1D element systems modelling pre-tensioned bolts (the model taken as "accurate" since it proved good consistency with lab tests results in terms of stress distribution within angle)
b) method 2.: bolt-disregarding approach ("tied" model) – with assumption that contacting element surfaces are tied over certain area. Two approaches are examined:
   - tied area is the total area of contact of both connected elements – "entirely tied" model,
   - tied area is the area of ring around each bolt shank; the inner and outer ring diameters are taken as hole and equivalent bolt head diameters respectively – "partially tied" model.

Method 1.

Each bolt model consisted of 2-node beam elements of 6 degrees of freedom per node and spring-type elements. The scheme of bolt model is given in Fig.3.

Bolt shanks ("a"–type line) were modelled with beam elements located along shank axis while bolt heads and nuts ("b"–type line) – with radially located beam elements joint together at nodes placed on bolt axis. The elements modelling bolt head (nut) were placed at the plane of contact, between bolt head (nut) and outer steel plate surface. The node in the centre of the radial system and respective outer node of extreme element modelling bolt shank were tied together by relative displacement conditions. Bearing of shanks against bolt holes walls was modelled with spring elements ("c"–type line) located at connected steel plates centre planes. Such arrangement of beam elements modelling each bolt head and spring elements allow for preserving actual steel plate thicknesses influence on bolt behaviour in the model.

Detailed description of bolt modelling method is given in [9]. Main features influencing stiffness of equivalent bolt model are as follows:

- nominal shank diameter is taken and actual tensile stiffness of bolt shank preserved,
- flexural "out-of-plane" stiffness of elements modelling bolt head and nut are based on results of comparative FEM analysis of beam-element-based and shell-element-based numerical models of bolt head,

– spring elements disregard tension while their compressive stiffness is based on results of analysis of part of shank of dimensions corresponding to wedge-shape 1/16-th of shank cross-section and to given steel plate thickness.

Pre-tensioning of bolts in FE models was introduced using "pre-tension section" input (available in Abaqus) for one beam element of each group modelling respective bolt shank.

Method 2.

Replacing bolts in FEM model by tying parts of contacting surfaces was considered. The regions (rings) around bolts, treated in such a way, are shaded in Fig.4. Inner and outer ring diameter was taken as hole and equivalent bolt head diameters respectively. Friction was defined over the rest of surfaces of angle leg and gusset plate in contact.

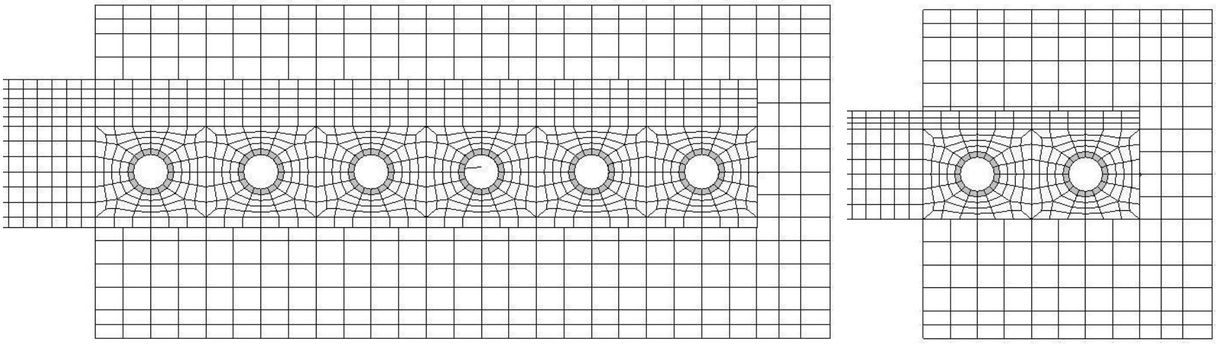

Fig.4. Tied parts (shaded) of surfaces in contact for specimens: S1 (left) and S11 (right)

In both methods Coulomb friction model available in Abaqus was applied. "Static" friction coefficient was taken as $\mu=0.25$ – in this approach the angle FE model behaviour is independent of velocity of its elongation increment.

Where necessary frictional contact, available in Abaqus, was applied with small-sliding" condition (i.e. assuming that slave surface nodes interact with the same local area of the master surface throughout the analysis). Surface-to-surface contact conditions were applied on surfaces where angle and gusset plate meet each other while node-to-surface contact conditions were used between nodes of beam elements representing bolt head (nut) and angle or gusset plate surfaces respectively.

General static analysis was chosen in Abaqus for the following two stages:

- stage I: nut tightening to achieve 200 kN pre-tensioning force in bolts, modelled numerically as assembly load,
- stage II: loading by quasi-static displacement of D-E edge of gusset plate along angle longitudinal axis: by 19 mm in the case of specimen S1 and by 9 mm in the case of specimen S11 (half of angle length was considered each time).

Numerical calculations were carried out in Poznan Supercomputing and Supernetworking Centre, using Abaqus Standard code [8].

4 TEST VERSUS NUMERICAL RESULTS

Fig.5 and 6 give computed and recorded longitudinal strains in angle flanges at critical cross-section, for specimen S1 and S11 respectively. Location of the critical cross-section (A–A) as well as strain gauges (1, 2, 3, 4) are given in Fig.2b. Positive strain means tension.

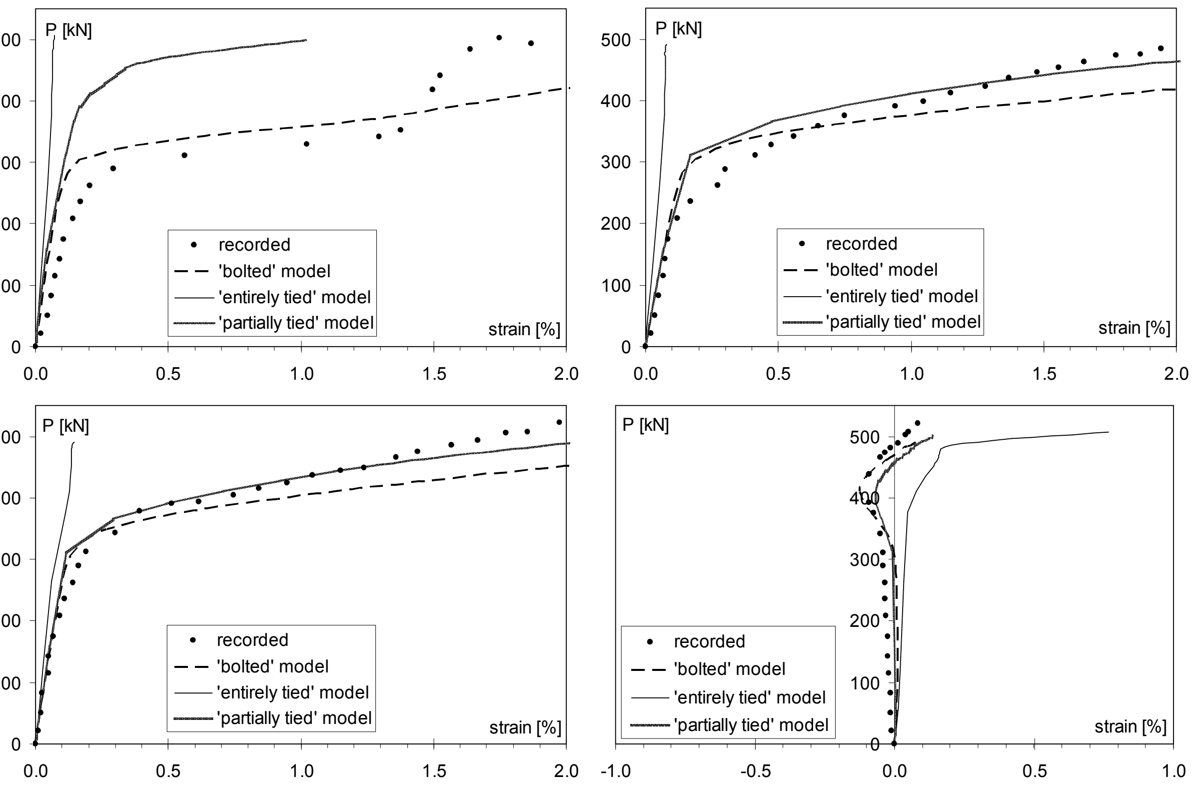

Fig.5. Computed and recorded longitudinal strains in angle flanges at A–A cross-section of specimen S1; gauge locations: *1* (top left), *2* (top right), *3* (bottom left), *4* (bottom right)

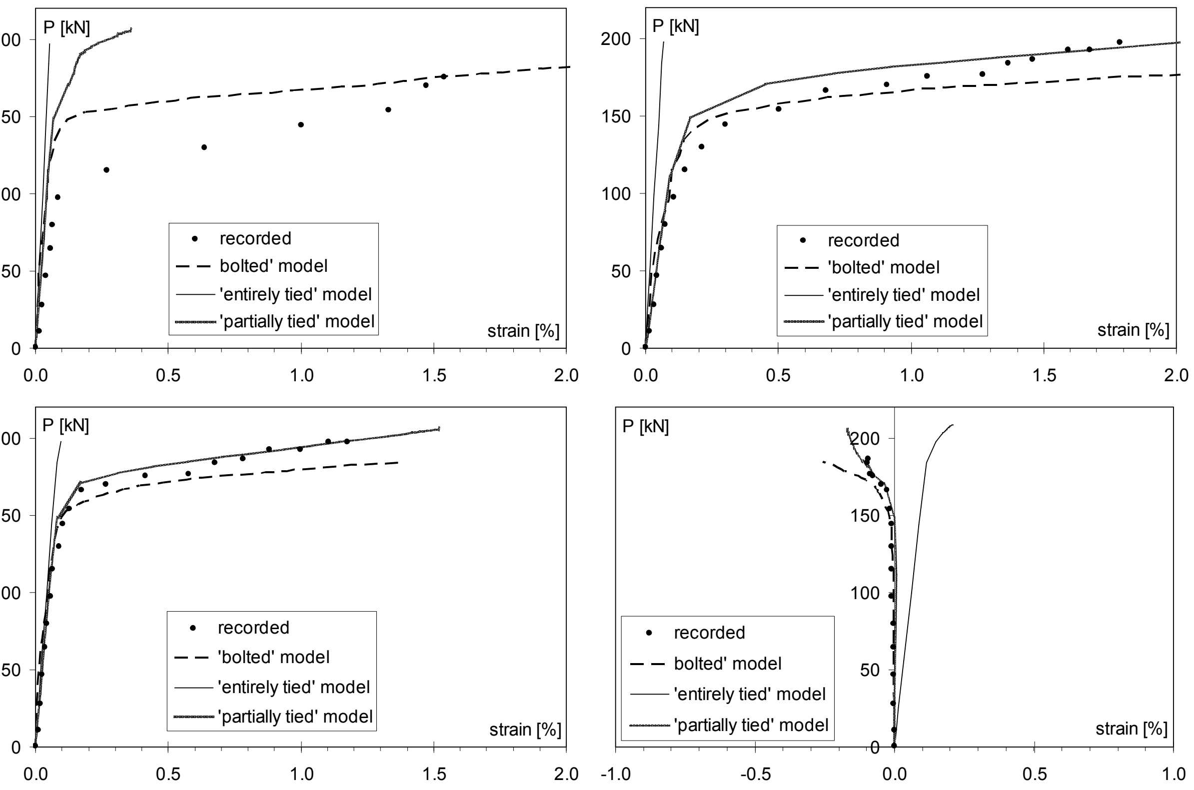

Fig.6. Computed and recorded longitudinal strains in angle flanges at A–A cross-section of specimen S11; gauge locations: *1* (top left), *2* (top right), *3* (bottom left), *4* (bottom right)

Again, the assessment of the strains in “bolted” and “partially tied” models is in general consistent with recorded data. The worst accuracy provides ‘entirely tied’ model.

The larges discrepancy is obtained for the strain gauge 1. It may resulted from slip of angle flange over gusset plate surface at the actual loading level that was lower than the computed one. Similar phenomenon may concern strain gauge 2.

Discrepancies between computed and recorded data increase with loading magnitude.

5 CONCLUSION

The paper shows some aspects of simplified modelling of friction grip bolted connections in shear. They may be especially applicable in large and geometrically complex connections with significant amount of bolts.

Modelling of friction grip bolted connections using simplified bolt modelling may be effective, especially in the case of analysis concerning elastic range. In such a case disregarding bolts and replacing them with “partially tied” modelling seems to be more attractive. It is less time-consuming and provides results of similar accuracy in comparison to analysis utilizing simplified bolt modelling.

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